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THE CRYSTALLIZATION
OF
IRON AND STEEL

AN INTRODUCTION TO THE STUDY OF METALLOGRAPHY

BY

J. W. MELLOR, D.Sc.

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DEDICATED TO MY FRIEND

A. E. BONE, Esq.

DUNEDIN, NEW ZEALAND

PREFACE

THIS course of six lectures—delivered to the Engineering Students of the Staffordshire County Technical Classes at the Newcastle High School, in November and December, 1904—was intended to summarize the results of the more important researches which have been made during the last ten years upon the constitution of alloys of iron and steel.

The claims of the new science—metallography—which has revealed the internal structure of the metallic alloys, have been too long overlooked. The far-reaching importance of this knowledge is beginning to dawn upon the most conservative minds. Metallurgists are now rending the veil which has so long concealed the internal structure of the metals and their alloys; and many phenomena connected with the industrial treatment of the metals, so long inexplicable, are now yielding up their secrets to the indefatigable methods of modern scientific research.

Unfortunately, much of this important work is disseminated throughout various scientific journals, and the facts are so frequently obscured beneath a mass of controversial matter that it is difficult for the uninitiated to get into touch with the work. In consequence, I have been lead to reproduce my lectures in a form suitable for publication, in the hope that they may help those who have not specially studied the subject to appreciate the remarkable chapter which metallurgists have recently added to physical chemistry.

I desire to thank Profs. Arnold, Beilby, Cohen, Ewing, Heyn, Newth, Osmond, Popplewell, and Stead for permission to use their micro-photographs; Dr. G. T. Beilby, the Secretary of the Iron and Steel Institute, the proprietors of *The Philosophical Transactions* and of *The Iron Age* for the loan of blocks; and Mr. H. Fowler for help with the diagrams.

J. W. MELLOR.

March 4, 1905.

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THE
CRYSTALLIZATION OF IRON AND STEEL

THE SOLIDIFICATION AND COOLING OF ALLOYS

§ 1. Atoms and Molecules

CHEMISTS have invested matter with an imaginary constitution, which explains very well the various transformations which matter undergoes. Matter is supposed to be made up of extremely small particles, called molecules. No successful attempt has been made to describe how the molecules associate together except in the case of crystalline substances. Here all the evidence points to a symmetrical and fixed mode of arrangement, which finally produces regular geometrical figures called crystals.

More or less approximate attempts to calculate the size of the molecules show that, if a drop of water were magnified to the size of the earth, the size of the molecules of water would be between that of small shot and of cricket balls. Molecules lie quite outside the range of observation, and we must accept here, in good faith, the large mass of circumstantial evidence accumulated by the chemist.

By analysis it has been found that the infinite variety of substances known to man can all be reduced to about eighty simple forms, called **elements.** No analyst has ever separated from an element anything but itself. Pure iron will yield nothing but pure iron. Iron is, therefore, an element. Pure copperas, on the other hand, will furnish iron, sulphur, and oxygen. Copperas is not an element. Facts like these seem to indicate that molecules are made up of still smaller particles. These are called **atoms.** Atoms of the same kind make up the molecules of elements; atoms of different kinds make up the molecules of compounds.

All substances known to man are supposed to be made up from different combinations of some eighty different kinds of atoms. Recent investigations seem to show that the different atoms are different combinations of still smaller particles, called **corpuscles,** or, if they be charged with electricity, **electrons.** All corpuscles are the same. Matter, whether it be a mummy, a piano stool, or a toothpick, is essentially one universal substance. Variety enters when the corpuscles arrange themselves in groups of atoms, when the atoms unite into molecules, and when the molecules aggregate into masses of matter. The stages are—

Corpuscles → atoms → molecules → matter *en masse.*

The molecules of a gas lead a more or less independent existence. This is illustrated by the rapidity with which the molecules of, say, ammonia gas travel from one end of a room to the other and affect the sense of smell. In liquids, however, the molecules are much less mobile. This can easily be proved by dropping a small grain of aniline dye into a tumbler of clear still water. The water will be uniformly coloured in a few days. The molecules of a solid substance have practically lost their mobility. But not all. Carbon laid in contact with pure, hot, solid iron will diffuse into the mass of the metal; and gold in contact with lead will, in a few years, diffuse into the lead in appreciable quantities.

§ 2. The Degradation of Energy

The infinite variety of changes continually taking place in the properties of bodies around us is often said to be due to the action of an external agent, called energy, upon matter. Just as water will always run down from a high to the lowest level that circumstances will permit, so will energy at a high potential always run down to energy at a low potential. And one of the most interesting phenomena in connection with all natural changes is this constant running down or degradation of energy. Still keeping the same analogy, just as water may descend from the top of a hill in many ways—rivers or rain, underground channels, glaciers, or avalanches—so may energy give rise to electrical, thermal, or chemical phenomena in its descent from a high to a low potential. But I need say little to engineers on this subject. The electric light, steam engine, electric tramcars, gas engines, water-wheels, watches, and clocks all bear testimony to the ubiquity of the law. An ancient philosopher has said that all things are in motion, and we might add that the motion always involves a degradation of energy. Motion only ceases when energy has run down to the level of its surroundings. The system is then said to be in a state of equilibrium.

§ 3. Passive Resistance

There is also another remarkable law—the law of passive resistance. Equilibrium may be apparent. The running down of energy may be resisted in some way. It is a common thing to find energy at a higher potential than we should expect. Energy does not always, of itself, run down to its lowest level. Just as the throttle-valve of a steam-engine must be moved before the degradation of high-pressure energy commences, and the engine can start on its journey, so may a preliminary impulse be required to set the process of degradation in motion.

We therefore distinguish between two states of equilibrium. The one is stable, the other unstable. The one is a real state of equilibrium, the other is only apparent. When you see water in a liquid state at a temperature below its normal freezing-point, 0° C., you know that some agent must be at work which prevents the freezing of the water. This unknown agent is called **passive resistance.**

Sodium thiosulphate is a convenient substance to illustrate these facts. At ordinary temperatures this salt is a white crystalline solid. On heating to 56° it melts to a clear liquid. This is also the freezing-point of the liquid. But it is possible to cool the molten salt down to the temperature of the room without solidification. The sodium thiosulphate is then said to be in a state of **apparent or false equilibrium,**

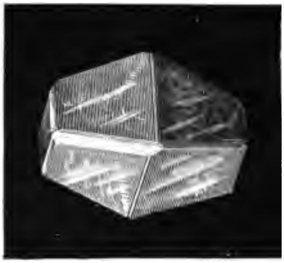

FIG. 1.—Octahedral Sulphur. (G. S. Newth.)

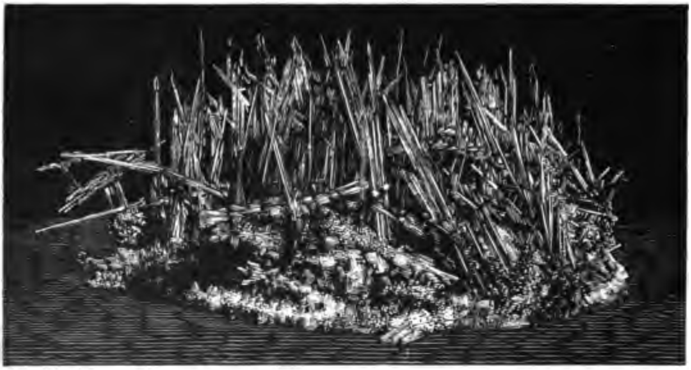

FIG. 2.—Prismatic or "Needle-shaped" Sulphur Crystals. (G. S. Newth.)

[*To face p.* 5.

and it can be kept in this state an indefinite time. Now put a crystal of sodium thiosulphate into the liquid mass. The passive resistance is overcome in some way, for now the liquid assumes the stable crystalline condition, and during the transition from the liquid to the solid states energy is degraded.

§ 4. Allotropy

Sulphur, at the temperature of this room, is a pale yellow crystalline solid. The crystals are shaped like octahedrons (Fig. 1). If sulphur be heated above 96°, these pass into needle-shaped crystals (Fig. 2). Still further, if sulphur be heated to near its boiling-point, and suddenly quenched by pouring into cold water, an amorphous, non-crystalline, plastic, and elastic mass is produced. Here, then, you have the element sulphur existing in three different forms—plastic, octahedral, and needle-shaped crystals. Each form is said to be an allotropic modification of sulphur.

This word allotropic. How can the same substance exist in different forms? Just as the builder can with the same kind of bricks build up various structures, so can Nature with the same kind of atoms build up molecules with very different properties. The atoms of sulphur, for instance, may form molecules which crystallize as octahedral or as needle-shaped crystals; atoms of carbon form three allotropic modifications—diamond, graphite, and amorphous carbon. *Allotropy occurs when a substance exists in two or more forms which differ in some of their properties.* The term is not usually applied to the different states of aggregation of a substance—solid, liquid, or gaseous. Allotropic transformations are usually accompanied by changes in the internal energy of the substance concerned. Energy is at a higher potential in one allotropic form than in another. The one form which has energy at the higher potential must be unstable.

§ 5. Transition Temperatures

The octahedral crystals are alone stable at ordinary temperatures. Both plastic sulphur and the needle-shaped crystals pass spontaneously into octahedral crystals at the temperature of the room. But above 96° the needle-shaped crystals are stable, while the plastic and the octahedral crystals slowly assume the needle-like form. You might just as well try to prevent water running down a hill as to prevent these changes taking place at these temperatures. Plastic sulphur will crystallize in octahedrons at the temperature of the room because the process involves the running down of energy. Sulphur, therefore, has two crystalline forms, one of which is stable above 96°, and the other below 96°. The critical temperature, 96°, is called the **transition temperature.**

Mercury iodide also exists in two allotropic forms, one of which is red and the other yellow. The red form is stable at ordinary temperatures, and passes into the yellow modification when heated above 126°. The yellow form is stable above 126°, but passes into the red form when cooled below the transition temperature, 126°.

After a particularly cold winter, 1867–68, some blocks of tin stored in the Customs House, and some tin buttons in the Military Stores at St. Petersburg had mysteriously crumbled to a grey powder. It has since been proved that tin exists in two allotropic

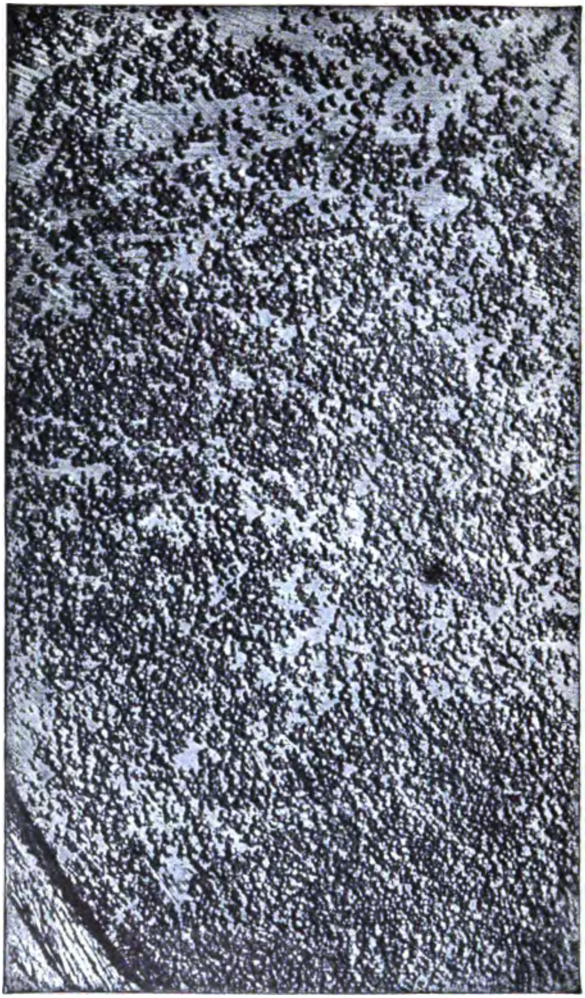

FIG. 3.—Surface of Diseased Tin. (E. Cohen.)

[*To face p.* 7.

modifications—white malleable metal, and grey powder. The transition temperature is 20°, just a little above the average temperature of the air. The grey powder is the stable form below 20°. Hence it follows that all the malleable tin in the world, except on the hottest summer days, is in an unstable condition. It is only passive resistance of some kind which prevents all the tin vessels in the world slowly crumbling to powdered grey tin.

§ 6. Velocity of Transformation

We have just seen that a crystal of sodium thiosulphate will make the unstable liquid thiosulphate pass into the stable form, so will the presence of a little grey tin facilitate the transformation of white into grey tin. This crumbling of tin to a grey powder is known as the *tin pest*. The disease is, therefore, infectious. The surface of a piece of diseased tin is shown in Fig. 3. The change is slow at ordinary temperatures. But articles of tin which have been buried a few hundred years are in almost every case in a more or less advanced state of disintegration.

The comparative rigidity or immobility of the molecules of a solid offers a kind of frictional resistance to change, analogous to the action of a brake upon the wheels of a car. If it were not for passive resistance the speed of transformation from one allotropic form to another would be faster the more distant the temperature away from the transition-point. Experiment shows that the rate of transformation of white into grey tin increases as the temperature is reduced below the transition-point, 20°. At −50°, for instance, the transformation is very rapid. As a general rule, passive resistance increases as the temperature falls below the transition-point. The one effect works against the other. If θ be the prevailing temperature, we may write—

$$\text{Velocity of change at } \theta^\circ = \frac{\text{transition temperature less } \theta}{\text{passive resistance at } \theta^\circ}$$

Or, if V denotes the velocity of transformation, R the magnitude of the passive resistance at θ°, and E the difference of the temperature between the transition point and θ°, we have—

$$V = \frac{E}{R} \cdot$$

a result which bears a close formal analogy with Ohm's well-known law. It may be assumed that E also represents the amount of energy to be degraded in the process. This formula states in symbols the observed facts that the greater the value of E, the greater the velocity of transformation; and the greater the value of R, the less the velocity.

These experiments teach us four important facts which must be clearly understood:—

(1) *A substance may exist in two or more forms having different properties.*

(2) *Only one of these forms is, in general, stable at any given temperature.*

(3) *The transformation of a substance from its unstable to its stable form occupies time.*

(4) *The transformation from the unstable to the stable form may be hindered or even arrested by passive resistance for an indefinite time.*

The phenomena are not always so obtrusive as the changes which take place with sulphur, tin, and mercury iodide. We naturally ask, how can we tell whether a substance is capable of existing in different allotropic forms? As a matter of fact, we select some physical property of the substance and measure it at different temperatures: if there is a sudden change in the physical property of the substance at any particular temperature, we infer that there is some drastic change going on in the internal structure of the substance.

§ 7. Cooling Curves

Let the temperature of a cooling copper bar at 200° be measured every ten minutes. Let distances at right angles to the line 0° – 200° (Fig. 4) represent time, and vertical distances from the line 0 – 60, the corresponding temperatures of the bar. We thus obtain the series of points shown in Fig. 4. Draw a line so as to lie most evenly among the points. The result is a so-called cooling curve. The simple form of the cooling curve in Fig. 4 gives no evidence of any sudden change in the nature of the cooling copper.

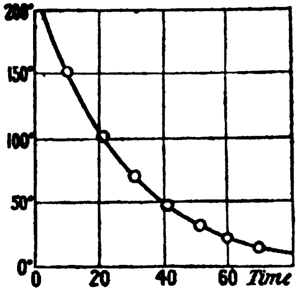

Fig. 4.—Cooling Curve of Solid Copper.

If a curve is drawn for water cooling down from

20° to −20° C., we get a terrace in the cooling curve, as shown in Fig. 5. This tells us that some change has taken place in the nature of the substance at 0°. We see directly that this change corresponds with the passage of water from the liquid to the solid state of aggregation.

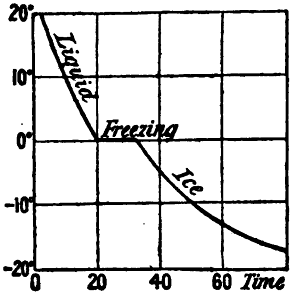

Fig. 5.—Water.

Now draw the cooling curve of molten sodium thiosulphate. We know that the molten liquid "ought" to freeze at 56° (Fig. 6). But the cooling curve goes on quite normally below that temperature until, at length, there is a great evolution of heat, and the liquid

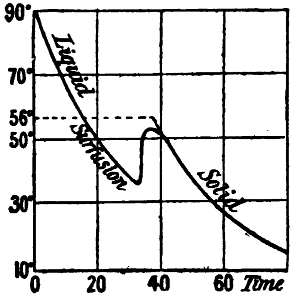

Fig. 6.—Sodium Thiosulphate.

solidifies. The temperature may even rise above 56°. The cooling curve of the solid is quite normal. The amount of heat evolved as the molten liquid solidifies corresponds with the "latent" heat absorbed as the solid melts.

§ 8. Surfusion and Recalescence

The molten sodium thiosulphate as it cools down the "surfusion" curve is at a lower temperature than its normal point of solidification or freezing. The liquid is then said to be in a state of superfusion or surfusion. The system is in unstable equilibrium. We may get a similar state of things when a saturated solution of a substance is slowly cooled. More salt may be in solution than the true solubility of the salt. The result is a supersaturated solution. Agitation, or the addition of a trace of something which will serve as a nucleus for crystallization, will generally suffice to start the system on its passage to a state of stable equilibrium. But when the transformation does set in, it usually takes place very rapidly, and is accompanied with a rise of temperature. The cooling curve is distorted in a corresponding manner (Fig. 6).

It is interesting to put a little ether in a small bulb blown at the end of a piece of glass tubing, placed in supercooled sodium thiosulphate (Fig. 7). Drop in a crystal of sodium thiosulphate. The evolution of heat as the liquid solidifies raises the temperature high enough to vaporize the ether. The vapour of ether will burn at the mouth of the tube with a steady flame when ignited.

When a steel bar is cooling, an evolution of heat occurs at about 690°. The amount of heat evolved is so great that the metal visibly brightens in colour.

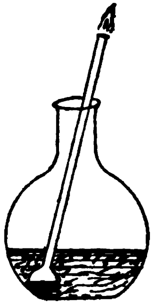

FIG. 7.

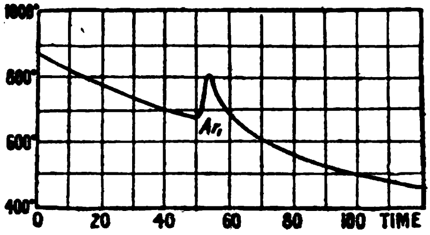

FIG. 8.—Recalescence.

The phenomenon is called recalescence. The cooling curve is shown in Fig. 8.

§ 9. The Cooling Curve of Pure Iron

The cooling curve of iron from the molten condition is shown in Fig. 9. The iron was practically pure. It

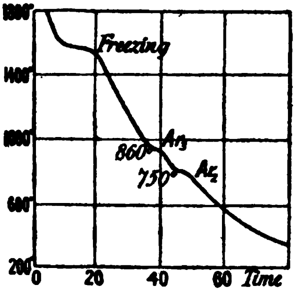

FIG. 9.—Iron.

only contained 0·01 per cent. of carbon. F. Osmond, a celebrated French metallurgist, maintains that the existence of the transition-points, or discontinuities, Ar_3 and Ar_2, in the cooling curve of the solidified metal, points to the existence of three allotropic modifications of solid iron:—

i. *Alpha Iron.*—Below Ar_2, that is 750°, we have what he calls α-iron, or alpha iron.

ii. *Beta Iron.*—Between Ar_2 and Ar_3, that is between 750° and 860°, we have what he calls β-iron, or beta iron. Beta iron is non-magnetic. Heat is evolved when iron passes from the β- to the α-state, and magnetic properties are developed at the same time.

iii. *Gamma Iron.*—Above the Ar_3 critical point, namely 860°, we are supposed to have γ-iron, or gamma iron. This variety is non-magnetic.

Each critical point is found to be associated with a change in the mechanical properties, the microscopic appearance, the electrical conductivity, the magnetic properties, and the specific gravity of the metal.[1]

The changes which occur during the cooling of a substance are reversed when the substance is heated. The cooling curve of steel, with 1·2 per cent. of carbon, shown in Fig. 10, is reversed on heating, as shown by the heating curve in the same diagram. There is only one critical point at about 690°, called the Ar_1 critical point.

The critical points Ac_1, Ac_2, Ac_3 on the heating curve of mild steel are generally a few degrees higher than the corresponding points Ar_1, Ar_2, and Ar_3 respectively. There seems to be a kind of molecular inertia, or lag, which prevents the γ to β, the β to a, or the reverse changes taking place sharply. The critical points on the cooling curve are, in consequence of this lag, a few degrees below the true critical point. The lag induces a state somewhat analogous to surfusion in molten sodium sulphate. The critical points on the heating curve are a little too high, and for a similar reason.[1]

---

[1] O. Boudouard, *Journ. Iron and Steel Inst.*, **63**. i. 229, 1903; H. le Chatelier, *Compt. Rend.*, **128**. 1444, 1899; **129**. 299, 331, 497, 1899; *Metallographist*, **2**. 334, 1899; **3**. 38, 152, 1900; G. E. Svedelius, *Phil. Mag.*, [5], **46**. 173, 1898; G. Charpy and L. Grenet, *Compt. Rend.*, **124**. 540, 598, 1902; *Metallographist*, **6**. 240, 1903; S. Curie, *ibid.*, 1. 107, 229, 1898.

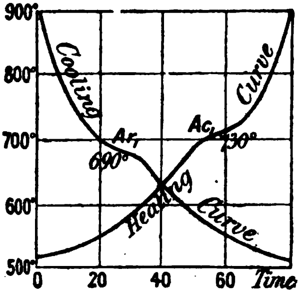

FIG. 10.—Steel.

The critical points of iron really represent ranges of temperature, although, for the sake of inconvenience, we call them points. The Ar_3 with soft steel commences at 845°, and finishes at 800°; it is most marked at 820°. The Ar_2 extends from 755° to 710°; and the Ar_1 from 680° to 645°.

The "r" of "Ar" comes from the French word *refroidissant*, for cooling; the "c" of "Ac" from *chauffant*, heating. This notation is due to D. Tschernoff,[2] the Russian metallographist.

---

[1] F. Osmond, *Metallographist*, 1. 270, 1893; 2. 169, 1899; H. M. Howe, *ibid.*, 2. 257, 1899; M. Aliament, *La Électricien*, 49, 1903.

[2] Otherwise spelt "D. Chernoff."

Now γ-iron is said to be hard, α-iron soft. If, therefore, γ-iron be quickly cooled past the Ar_2 critical point, the passage of the hard γ-iron to the soft α-iron is retarded; the iron is then in an unstable hardened condition, ready on the least provocation to pass into the stable soft α-form.

We naturally ask is there any method of helping the passive resistance so that the iron will not readily change from, say, the γ to the α modifications at ordinary atmospheric temperatures? It is supposed that the presence of many foreign substances, like carbon, nickel, and manganese, augment the passive resistance so as to render the hard γ-iron more stable and permanent at low temperatures. On the other hand, the presence of chromium, tungsten, aluminium, silicon, phosphorus, arsenic, and sulphur facilitate the passage of hard beta[1] iron to the soft alpha iron.

The influence of minute traces of foreign substances upon the properties of the metals is a most important subject. The effects seem inexplicable. The presence of 0·05 per cent. of tellurium alters the properties of bismuth so much that we seem to be dealing with a totally different substance; a few hundredths of one per cent. of sulphur will determine the success or failure of iron; and the presence of 0·1 per cent. of bismuth in copper lowers its conductivity so much that if copper so contaminated had been alone available, it would have been fatal to the success of the Atlantic cable.

---

[1] Either "gamma" or "beta." We are not sure which. Both are supposed to be hard.

§ 10. The Freezing of Salt Water

I have been speaking of pure or almost pure iron, and now we naturally turn to alloys of iron with carbon. Cast iron and steel are, as you well know, alloys or solidified solutions of carbon in iron. These alloys are so complex that it will be profitable for us to examine some other solutions which do not present such complications as occur in the case of the iron-carbon alloys. It is a most interesting fact to find that the same general laws hold good for the cooling of metallic alloys, for the separation of ice when sea water is frozen, the separation of crystals in the glazes of the potter, the devitrification of old glass, for alloys of carbon and iron, and the formation of rocks when the world was a-building. True enough, with the iron-carbon alloys other phenomena are superposed upon, and hence modify the course of the simple phenomenon as it occurs during the freezing of sea water.

The freezing-point of a 5 per cent. solution of sodium chloride is below that of pure water. If more salt be added, the freezing-point is reduced still more; and this goes on until the solution contains 23½ per cent. of sodium chloride, when further additions of salt raise the freezing-point. The experimental results are shown in Fig. 11.[1]

But the experiment reveals something more interesting than this. If the solution contains, say, 5 per cent. of salt, pure ice separates out as the solution freezes, and, in consequence, the solution which remains unfrozen has more than 5 per cent. of salt dissolved in it. The freezing-point of the mother liquid is therefore lower than that of the original solution. This separation of pure ice, and the lowering of the freezing-point, goes on along the curve *AP* (Fig. 11), until the solution contains 23½ per cent. of salt. After that, the residual mixture freezes *en masse* at −22°.

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[1] F. Guthrie, *Phil. Mag.*, [5], 1. 354, 1876.

If the solution contains more than 23½ per cent. of salt, then pure salt separates from the solution, and the separation of salt, and the lowering of the freezing-point of the solution goes on along the curve *BP* (Fig. 11), until the solution contains 23½ per cent. of salt, and the whole residue then solidifies at −22°.

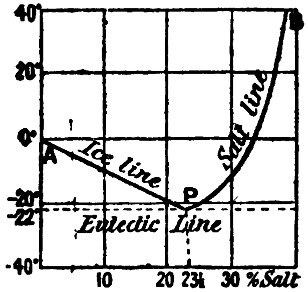

FIG. 11.—Freezing Curves of Aqueous Salt Solutions.

If the solution contains just 23½ per cent. of sodium chloride, it freezes *en masse* at −22°. No other mixture of salt and water freezes at a lower temperature than this. Hence this mixture is called a eutectic mixture. Guthrie used to think that the mixture which separated at this temperature was a definite chemical compound of water with salt, which he called a cryohydrate. Ponsot calls the mixture a "cryosel." The term eutectic mixture is to be preferred. We know now that Guthrie's cryohydrate is nothing but a mechanical mixture of ice and salt. The one is entangled with the other. Under the microscope the crystals of ice can be seen lying in a matrix of salt.[1]

§ 11. The Solidification of Copper-Silver Alloys

A like phenomenon occurs when molten mixtures of silver and copper are allowed to cool. At 770°, when the alloy has the composition 28 per cent. of copper and 72 per cent. of silver, the whole solidifies *en masse*. If the mixture contains less than this percentage of copper, pure silver separates at temperatures along the "silver" line (Fig. 12); while, if the molten mixture contains more than 28 per cent. of copper, pure copper separates, and continues separating along the "copper" line until the mixture has the above composition, when the whole solidifies as a eutectic mixture at 770°. No other alloy of silver and copper

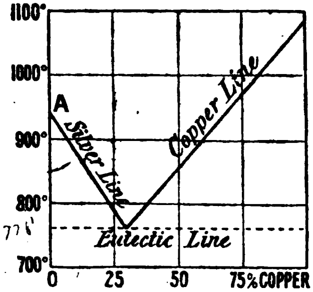

Fig. 12.—Fusibility Curves of Copper-Silver Alloys.

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[1] A. Ponsot, *Ann. Chim. Phys.*, [7], 10. 79, 1897; T. Andrews, *Proc. Roy. Soc.*, 40. 544, 1890; 48. 106, 1890; J. Y. Buchanan, *Proc. Roy. Soc. Edin.*, 14. 129, 1888.

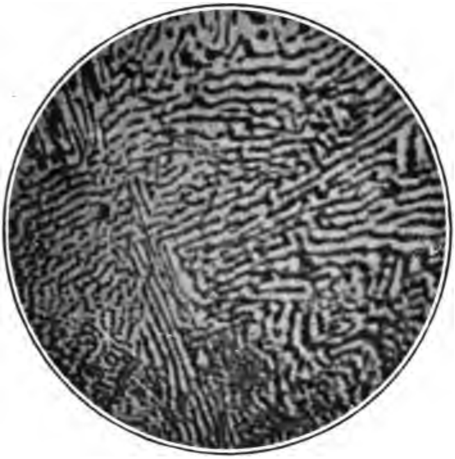

FIG. 13.—Polished Surface of Cu-Ag Alloy. (F. Osmond.)

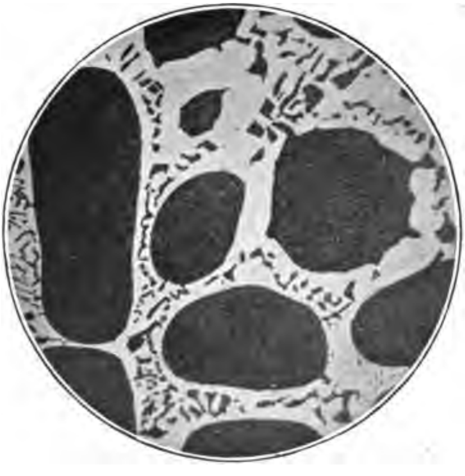

FIG. 14.—Polished Surface of Cu-Ag Alloy. (F. Osmond.)

[*To face p.* 19.

melts at so low a temperature. The resulting alloy is a network of the two metals, pure silver and pure copper, as shown in Fig. 13, where the heterogeneous nature of the alloy is clearly seen. In Fig. 14 we have an alloy of 15 per cent. of copper and 85 per cent. of silver. The alloy has a greater percentage of silver than the eutectic alloy, and in consequence silver separates out until the residue has the eutectic composition. This is in harmony with the microscopic appearance of the alloy, which shows large masses of silver embedded in a network of the eutectic alloy.

An alloy of these metals appears to possess two freezing-points: (i.) The temperature at which the mass begins to solidify; and (ii.) the temperature at which the whole is solidified. The pasty condition of solder—tin with 66 per cent. of lead—is due to the fact that there are two freezing-points. Solid lead separates first, and on this fact depends the facility with which a joint can be wiped with plumber's solder.

We get similar results with binary alloys of antimony and lead, tin and lead, tin and bismuth, tin and zinc, lead and silver, zinc and aluminium, and with copper and gold.[1]

The fusibility curve is very much simpler if the one constituent is mutually soluble in the other in all proportions. The fusibility curve is then approximately a straight line (*AB*, Fig. 15). This is the case with alloys of silver and gold. The same thing occurs with alloys of antimony and bismuth.

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[1] W. Campbell, *Journ. Franklin Inst.*, **154**. 1, 131, 201, 1902; *Metallographist*, **5**. 286, 1902; J. E. Stead, *ibid.*, **5**. 110, 1902; H. M. Howe, *ibid.*, **5**. 166, 1902; A. W. Kapp, *Drude's Ann.*, **6**. 754. 1901; W. C. Roberts-Austen, *Proc. Roy. Soc.*, **23**. 481, 1884; **63**. 452, 1898; G. T. Heycock and F. H. Neville, *Phil. Trans.*, **189**. 25, 1897; A. Dahms, *Wied. Ann.*, **54**. 486, 1895; H. le Chatelier, *Compt. Rend.*, **118**. 350, 415, 800, 1894.

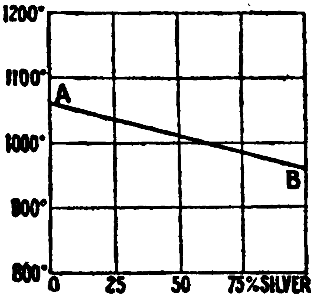

Fig. 15.—Fusibility Curve of Gold-Silver Alloys.

§ 12. The Solidification of Copper-Antimony Alloys

Silver and copper do not form a chemical compound. Many metals, however, do form compounds. Copper and antimony, for example, form a compound having the chemical formula $SbCu_2$, or, according to H. le Chatelier, Sb_2Cu_3. This behaves as if it were a single and distinct element. The addition of either copper or antimony lowers the melting-point of the compound $SbCu_2$ in the ordinary way. In Fig 16, *C* represents the melting-point of the pure compound $SbCu_2$. The line CP_1 represents the effect of the addition of antimony to the compound; while the line CP_2 represents the effect of additions of copper. There are two eutectic points, the one, P_2, corresponding with the eutectic mixture of the compound $SbCu_2$ with copper,

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[1] A. Gautier, *Bull. Soc. d'Encouragement*, [5], 1. 1293, 1896; W. C. Roberts-Austen, *Proc. Roy. Soc.*, 67. 105, 1900; with T. K. Rose, 71. 161, 1903.

and the other, P_1, corresponding with a eutectic mixture of $SbCu_2$ with antimony.

The results depicted in Figs. 11, 12, and 16 can be represented graphically in another way.[1] Take the more complicated case (Fig. 16). Let the horizontal line (Fig. 17) represent the ultimate composition of the alloy in terms of copper; the vertical lines, the structural composition in terms of the various constituents—copper, $SbCu_2$, antimony, or the two eutectics. As an example, an alloy with 10 per cent. of copper will have 40 per cent. of the first eutectic

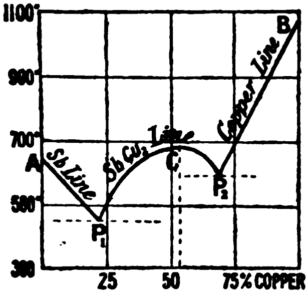

FIG. 16.—Fusibility Curve of Copper-Antimony Alloys.

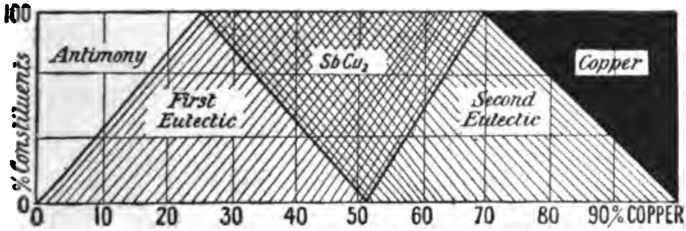

FIG. 17. (After A. Sauveur.)

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[1] A. Sauveur, *Metallographist*, 1. 103, 1898.

and 60 per cent. of antimony; an alloy with 33 per cent. of copper will have 30 per cent. of the first eutectic, and 70 per cent. of $SbCu_2$.

Alloys of gold and antimony present similar phenomena.[1]

§ 13. The Cooling of Iron-Carbon Alloys

But we can go a step further. Let us consider what takes place when an iron bar containing, say, 0·6 per cent. of carbon and 99·4 per cent. of iron cools from 900°. The cooling curve shows nothing very remarkable until a temperature of about 720° is attained. There is then a sudden evolution of heat. The critical points, Ar_3 and Ar_2, of pure iron coalesce into one. At this point pure iron, or ferrite, as Howe calls it, separates from the solid solution. The separation of ferrite goes on along the curve *AP* (Fig. 18) until the temperature reaches about 660°,

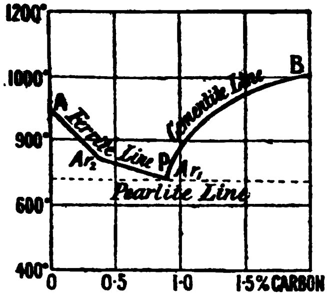

FIG. 18.—Cooling of "Solid Iron."

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[1] C. T. Heycock and F. H. Neville, *Proc. Roy. Soc.*, 68. 171, 1901; J. E. Stead, *Journ. Soc. Chem. Ind.*, 17. 1111, 1898; *Metallographist*, 1. 179, 1898; 2. 314, 1899; G. Charpy, *ibid.*, 1. 87, 192, 1898.

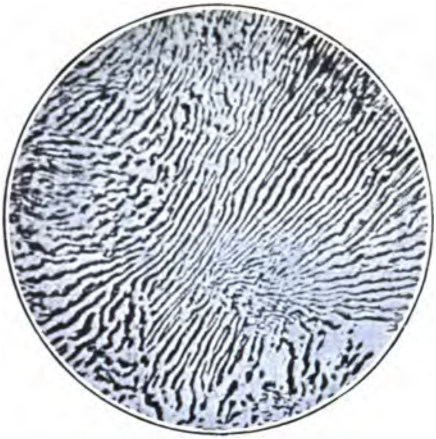

Fig. 19.—Surface of Lamellar Pearlite. (F. Osmond.)

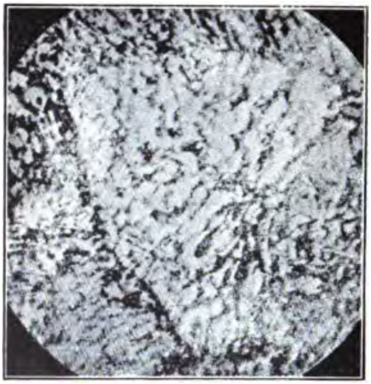

Fig. 20.—Surface of Granular Pearlite. (E. Heyn.)

[*To face p.* 23.]

when another recalescence point occurs (Ar_1). No other noteworthy change occurs as the system cools down to the normal temperature of the atmosphere. Other alloys containing different amounts of carbon furnish a set of curves quite analogous to the freezing curves of salt water and of silver-copper alloys. But with iron these changes take place in the *solid* cooling metal.

If the alloy contains less than 0·89 per cent. of carbon there is a separation, or, better, segregation of ferrite; if the alloy contains more than 0·89 per cent. of carbon, there is a separation, not of carbon, but of a chemical compound of carbon with iron, called normal iron carbide, or cementite, and represented in chemical symbols by Fe_3C. Cementite contains 6·9 per cent. of carbon. The separation of cementite occurs along the curve *BP* (Fig. 18). We are therefore dealing with a mixture of ferrite and of cementite. The eutectic alloy contains 13 per cent. of cementite (*i.e.* 0·89 per cent. of carbon) and 87 per cent. of ferrite—roughly, six of ferrite to one of cementite. The microscopic appearance of the eutectic reminds one forcibly of other eutectic mixtures. The eutectic mixture of cementite and ferrite is called pearlite, owing to the fact that it generally shows the rainbow tints of mother-of-pearl under microscopic treatment. Sorby called it the "pearly constituent" of steel.

Fig. 19 shows a fine specimen of lamellar pearlite obtained from a steel containing 1·0 per cent. of carbon. The black streaks are ferrite. Fig. 20 shows a specimen of what is sometimes called granular pearlite, from a

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[1] According to H. le Chatelier, *Journ. Iron and Steel Inst.*, 61. i. 40, 1902, there are two or three allotropic forms of cementite.

forged bar of crucible steel containing 0·92 per cent. of carbon. It is magnified 1240 times.

§ 14. Colour Names for High Temperatures

I always speak of temperatures on the centigrade scale. For reference purposes I will give a scale of corresponding centigrade and Fahrenheit temperatures, and also the colour names as determined by White and Taylor with the Le Chatelier pyrometer.[1] These results are said to be more accurate than Pouillet's old numbers.

The colour names do not really correspond with any particular temperature, but rather with a certain range of temperature. The results, too, depend upon so many external factors—physical and physiological—that different numbers might be obtained by different observers, and by the same observers at different times.

° C.	° F.	Colour names.
532	990	Dark blood red, black red, incipient red, rouge naissant.
566	1050	Dark red, blood red, low red, rouge sombre.
635	1175	Dark cherry red, incipient cherry red, cerise naissant.
682	1250	Medium cherry red.
746	1375	Cherry, full red, cerise.
835	1550	Light cherry, bright cherry, scaling heat,[2] light red, cerise clair.
899	1650	Orange, salmon; free scaling heat, orange foncée.
941	1725	Light orange, light salmon, orange clair.
996	1825	Yellow.
1079	1975	Light yellow.
1205	2200	White, blanc.

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[1] M. White and F. W. Taylor, *Metallographist*, 3. 41, 1900; H. M. Howe, *ibid.*, 3. 43, 1900; C. S. M. Pouillet, *Compt. Rend.*, 3. 784, 1836.

[2] Scale forms and adheres,—*i.e.* does not fall away from the piece when cooled in air.

There is also a colour scale of temperatures used in the tempering and annealing of iron. The colours are due to the formation of a thin film of oxide on the surface of the metal.

° C.	° F.	Colour names.
220	408	Faint yellow.
230	446	Straw yellow.
255	491	Brownish yellow.
265	509	Purple brown.
277	531	Purple.
280	536	Violet.
288	550	Light blue.
293	559	Dark blue.
316	601	Blackish blue.
400	732	Black.

THE CONSTITUENTS OF IRON AND STEEL

§ 15. Eutexia

THE phenomenon of eutexia, as we have seen, plays a most important part in the structural changes which take place during the cooling of iron. Figs. 11, 12, and 16 abbreviate in one diagram the cooling curves of every possible mixture of the two components concerned. Eleven cooling curves of silver-copper alloys, containing various proportions of the two metals, are shown in Fig. 21; and when arranged in this manner

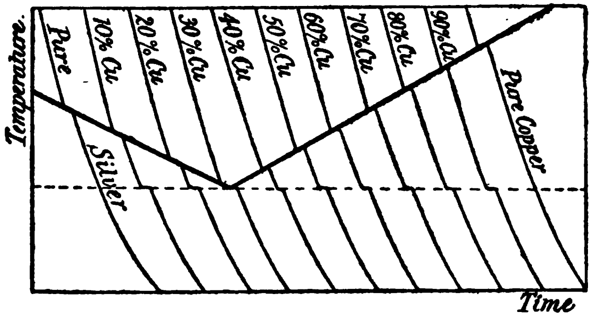

FIG. 21.—Set of Cooling Curves of Ag-Cu Alloys.

you can see the genesis of the eutectic diagrams without further study.

I hope that you can trace the analogy between the freezing of salt water, the solidification of silver-copper alloys, and the cooling of steel bars. Let me attempt a comparison of the cooling of steel with the freezing of a solution of salt and water, leaving you to extend the comparison to the solidification of the copper-silver alloy.

Solution of salt and water.	Iron-carbon alloy.
1.—Larger per cent. of water than the eutectic mixture. Crystals of ice in cryohydrate.	1.—Larger per cent. of iron than the eutectic mixture. Crystals of ferrite in pearlite.
2.—Larger per cent. of salt than the eutectic mixture. Crystals of salt in cryohydrate.	2.—Larger per cent. of carbide than eutectic. Grains or bands of cementite in pearlite.
3.—Same composition as eutectic mixture (23½ per cent. of salt). Solidifies at −22° as network of ice and salt, *i.e.* of the cryohydrate.	3.—Same composition as eutectic mixture (0·9 per cent. of carbon). System consists entirely of lamellar or granular pearlite.

§ 16. The Relative Proportions of Ferrite, Cementite, and Pearlite

The remarkable analogy which obtains between the constitution of steel and of a crystalline igneous rock was first pointed out by H. C. Sorby, of Sheffield, in 1864.[1] In granite, for instance, we have certain specific constituents of definite chemical composition—mica, feldspar, and quartz; while in the iron-carbon alloys there are also two well-defined constituents—ferrite or pure iron, cementite or iron carbide—and the eutectic mixture, pearlite.

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[1] H. C. Sorby, *B. A. Reports*, ii. 189, 1864; i. 139, 1865; *Journ. Iron and Steel Inst.*, **29**. i. 140, 1886; **33**. i. 255, 1888. "Steel," said Sorby, "must be regarded as an artificial crystallized rock, and to get a complete knowledge of it, it must be regarded as such."

All three constituents were discovered by Sorby, and their present names were suggested by Howe. They segregate from the cooling solid according to the laws just outlined, and they can be readily seen when a polished surface of the alloy is examined under the microscope. If large tracts of ferrite be present, the alloy contains less than 0·89 per cent. of carbon; while if large areas of cementite be present, the alloy contains more than 0·89 per cent. of carbon. Fig. 22 shows

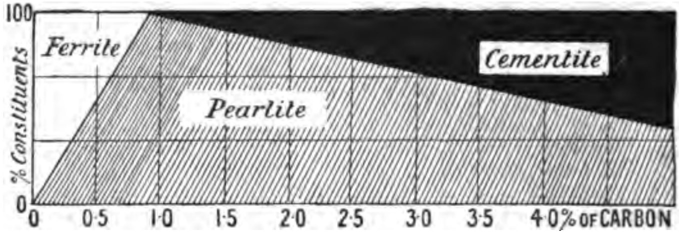

FIG. 22. (After A. Sauveur.)

diagrammatically the relation between the percentage of combined carbon, and the percentage amounts of the constituents—ferrite, cementite, and pearlite—in various steels and cast irons. The diagram shows, for example, that a steel containing 0·5 per cent. of carbon has nearly 58 per cent. of pearlite, and 42 per cent. of ferrite; cast iron containing 3·5 per cent. of carbon has 62 per cent. of pearlite, and 38 per cent. of cementite. Eutectic, or saturated, steel, composed wholly of pearlite, has 0·9 per cent. of carbon; a steel containing less than this amount of carbon is said to be a hypo-eutectic, or unsaturated, steel; while if the steel

has more than 0·9 per cent. of carbon, it is said to be a hyper-eutectic, or supersaturated, steel.

NOTE.—*To calculate the amount of pearlite and excess ferrite or excess cementite in steel containing a given percentage of carbon,* assuming that the iron has been cooled slowly, so that everything is in equilibrium. The formulæ are deduced by the ordinary methods used in chemical computations.

I.—*Hypoeutectic or unsaturated steels* (ferrite in excess).

Per cent. of cementite in pearlite = 15 × per cent. of carbon . . (1)
" ferrite in pearlite = 6·4 × per cent. of cementite . . (2)
" pearlite = per cent. ferrite + per cent. cementite . . (3)
" excess ferrite = 100 – per cent. pearlite . . . . (4)
" total ferrite = per cent. excess ferrite + per cent. ferrite in pearlite . . . . (5)

II.—*Eutectic steels* (0·9 per cent. of carbon), pearlite alone present. Only (1) and (2) is required for the calculation.

III.—*Hypereutectic or supersaturated steels* (cementite in excess).

Per cent. of total cementite = 15 × per cent. of carbon . . . . (6)
" ferrite in pearlite = 100 – per cent. of total cementite (7)
" cementite in pearlite = per cent. of ferrite ÷ 6·4 . . (8)
" pearlite = per cent. cementite + per cent. ferrite . . (9)
" cementite in excess = per cent. total cementite – per cent. in pearlite . . . . (10)

EXAMPLES.—(1) A low carbon steel has 0·1 per cent. of carbon. What are the percentage amounts of the constituents? Obviously the ferrite will be in excess, and there will be—

15 × 0·1 = 1·5 per cent. of cementite in pearlite.
6·4 × 1·5 = 9·6 per cent. of ferrite in pearlite.
1·5 + 9·6 = 11·1 per cent. of pearlite.
100 – 11·1 = 88·9 per cent. of ferrite in excess.
88·9 + 9·6 = 98·5 per cent. of total ferrite.

(2) Calculate the percentage amounts of the various constituents of white cast iron containing 2 per cent. of carbon. The cementite will be in excess, and there will be—

15 × 2 = 30 per cent. of cementite.
100 – 30 = 70 per cent. of ferrite.
70 ÷ 6·4 = 10·9 per cent. of cementite in pearlite.
10·9 + 70 = 80·9 per cent. of pearlite.
30 – 10·9 = 19·1 per cent. of cementite in excess.

§ 17. Graphitic, Hardening, and Cement Carbon

Molten iron can dissolve as much as 7 per cent. of carbon. The amount dissolved depends upon the temperature. At the eutectic temperature, between 1100° and 1200°, the molten solution contains 4·3 per cent. of carbon; and the eutectic mixture when solidified has 2·3 per cent. of carbon in the form of graphite. The carbon which is rejected as the molten solution cools is called **graphitic carbon.** The separation of graphitic carbon goes along the line *BP* (Figs. 24 and 25).

Graphitic carbon is found almost exclusively in cast iron. It is not acted upon by boiling hydrochloric acid, nor by nitric acid (sp. gr. 1·2). The graphite which is formed during the solidification of the alloy is generally in the form of thin plates or flakes, often one-eighth of an inch or more in thickness, as shown in Fig. 23, which represents a specimen of grey pig iron with 0·72 per cent. of silicon, magnified 90 diameters. The rounded areas consist of cementite surrounded by depressed pearlite.

About 1822, Faraday and Caron noticed that the carbon in quenched and annealed steels, containing no graphitic carbon, exists in two distinct forms. One kind, called **hardening carbon,** escapes as hydrocarbon gas when steel is digested with dilute hydrochloric or sulphuric acid; the other form of carbon—**cement carbon, or cementite carbon**—is left as an insoluble residue when steel is digested in the acids just named. Cement carbon dissolves in dilute nitric acid to form a brown solution, which is utilized in the well-known Eggertz's colour test for combined carbon.[1]

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[1] H. Jüptner von Jonstorff, *Journ. Iron and Steel Inst.*, 51. i. 248,

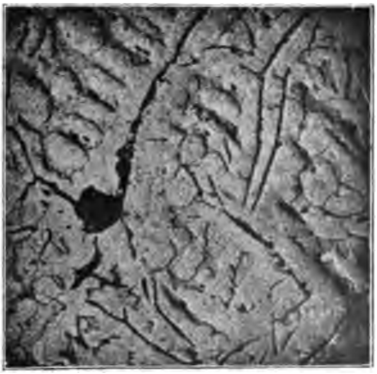

FIG. 23.—Graphite in Grey Pig Iron. (E. Heyn.)

[*To face p.* 30.

It is interesting to notice that the presence of chromium in steel seems to stimulate the formation of hardening carbon, and to prevent the latter passing into cement carbon. The special property of chrome steels is extreme hardness. Chromium appears not to confer hardness upon steels in the absence of carbon.

We do not know in what form hardening carbon exists in steel. It may be simply a solid solution of carbon in iron. What is a solid solution?

§ 18. Compounds, Mixtures, and Solutions

There are two special features about chemical compounds which it is well to notice. The elements which make up a chemical compound are so completely merged one in the other as to form a new substance having properties quite distinct from any of its components. Neither by the microscope nor by any other known means is it possible to detect the components of the compound so long as the compound retains its individuality. In copper oxide, for example, the components—copper and oxygen—are absolutely indistinguishable. The compound is quite homogeneous. The second feature is that the elements are combined together in certain fixed and definite proportions. In black copper oxide there are 63·5 parts of copper for every 16 parts of oxygen; in red copper oxide, 127 parts of copper are united with 16 parts of oxygen. Copper and oxygen unite in no other proportions.

On the other hand, in glass, the lime, soda, and silica are united together so as to form a perfectly

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1897; *Metallographist*, 1. 154, 1898; Report with A. A. Blair, G. Dillner, and J. E. Stead, *Journ. Iron and Steel Inst.*, 66. ii. 221, 1904.

homogeneous mass. The constituents are merged together as if the glass were a true chemical compound. But glass does not satisfy the second criterion. The constituents can be mixed in many different proportions. The amounts of silica or lime can be varied between wide limits and still produce glass. Glass may be called a **solid solution** in contradistinction to ordinary **liquid solutions**, like whiskey and water, or salt and water. Solutions satisfy the first but not the second mark of chemical compounds.

The components of an ordinary mixture are not so completely merged as in chemical compounds. The constituents of a mixture can generally be separated by mechanical means, and they may be mixed together in any proportions we choose. In a **eutectic mixture**, however, the constituents are mechanically mixed together in fixed and constant proportions. To summarize, a given substance may be—

Heterogen.	Indefinite proportions			Ordinary mixture.
	Definite proportions			Eutectic mixture.
Homogen.	One component			Element.
	More than one	Def. proport.		Chem. compounds.
		Indef. proport.	Liq.	Solution.
			Solid	Solid solution.

The terms "isomorphous mixture" and "mixed crystals" are not to be used in place of "solid solution." Isomorphous salts are those which furnish crystals having the same shape or form; isomorphous substances will frequently crystallize together to form single crystals, called **mixed crystals.**

A solidified solution, although it be a solid, may yet retain the essential characteristics of a liquid solution.[1] Of course, a solidified solution is not necessarily a solid solution. As a general rule a solvent can dissolve more of any constituent the higher the temperature. At any given temperature there is usually a limit to the amount the solvent can dissolve. If a solution is saturated at any given temperature, then, on cooling, the solution will reject all in excess of the maximum amount it can dissolve at the lower temperature. The solution theory of carbon-iron alloys affirms that—

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[1] V. Rothmund, *Zeit. phys. Chem.*, 26. 483, 1897.

1. Molten carburized iron is a solution of carbon in iron.
2. The solidified mass is a solid solution.
3. The molten and solid solutions obey the laws of ordinary fluid solutions.[1]

§ 19. The Solidification of Molten Iron

Let us examine in more detail a freezing solution of carbon and iron. The freezing curves are shown in Fig. 24. If molten iron containing less than 4½ per cent. of carbon be cooled, a solid solution of carbon in iron begins to separate along the line AP' (Fig. 24). This solid solution of carbon in iron is called **martensite**, in honour of the German metallurgist, A. Martens.[2] There is a complication. The solid solution of carbon in iron which separates is not a definite chemical compound. The iron will not retain, in solid solution, more than 2 per cent. of carbon, whereas the molten mass may have as much as 4½ per cent. of carbon. We have a new curve (AQ, Fig. 24).

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[1] A. S. Stansfield, *Metallographist*, **3**. 24, 300, 1900; *Journ. Iron and Steel Inst.*, **56**. ii. 169, 1899; **58**. ii. 317, 1900.

[2] W. C. Roberts-Austen, *Metallographist*, **2**. 186, 1899.

The abscissa, at any point on the curve *AQ*, represents the compositions of the *solid*, which separates when the *solution* has the composition represented by the abscissæ of the curve *AP′* corresponding with the *same* ordinate. For example, the *solid* which separates at the temperature *OT* has the composition *TS*, while the composition of the freezing *liquid* is represented by *TR*. The eutectic mixture which separates at *P′* consists of graphite associated with martensite having the composition represented by *MQ*. As the iron cools down from the eutectic temperature *OM*, the solid martensite rejects more carbon. The curve *QN* is the solubility curve of carbon in iron. When the temperature falls to 1000°, the solid solution, martensite, only contains *ON*—that is, 1·8 per cent. of carbon. The carbon which separates out from the solid metal at temperatures below the point of solidification is usually in the form of a very fine powder, and it is called temper carbon, temper graphite, or annealing carbon. Graphite, you will remember, is an allotropic modification of carbon.

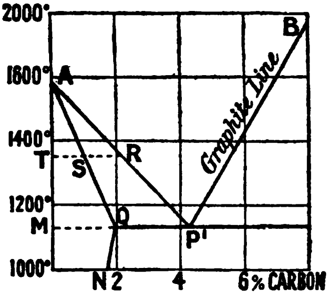

FIG. 24.—Fusibility Curves of Iron-Carbon Alloys.

Roozeboom[1] has collected the results depicted in diagrams Figs. 18, 22, and 24 into one diagram, shown, slightly modified, in Fig. 25. Here *P* is the eutectic point of Fig. 18, and *P′* of Fig. 24. Fig. 25 may be taken provisionally to represent the relation

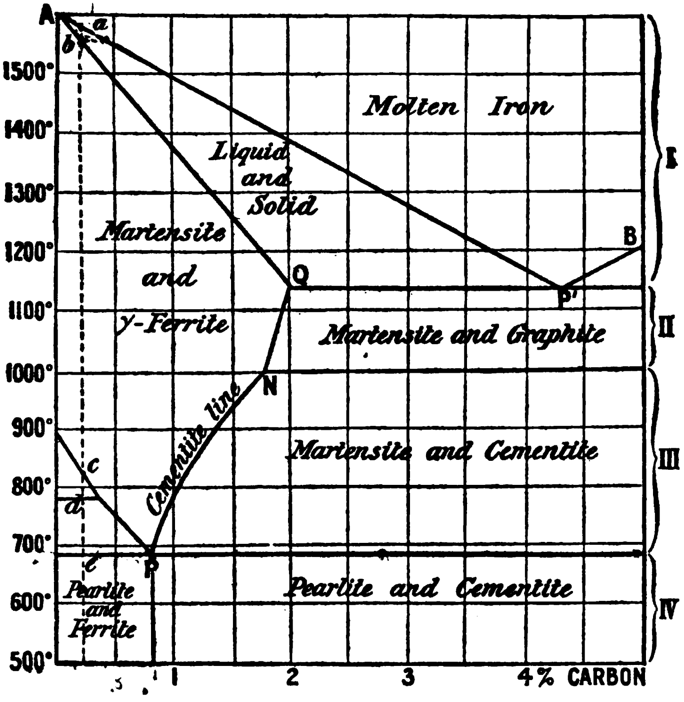

Fig. 25.—Diagrammatic. (After H. W. B. Roozeboom.)

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[1] H. W. B. Roozeboom, *Zeit. Phys. Chem.*, 34. 437, 1900; improved in *Zeit. Elektrochem.*, 10. 489, 1904; *Metallographist*, 3. 293, 1900; H. le Chatelier, *ibid.*, 3, 290, 1900; 4. 161, 1901; F. Osmond, 4. 150, 1901; H. Jüptner von Jonstorff, *ibid.*, 5. 210, 1902.

between the various constituents and the temperature, when the system is in stable equilibrium.[1] Owing to the lack of suitable measurements, some of the curves are only approximately known. After what has been said, I think one example will be sufficient to illustrate the use of the diagram. Take a steel with 0·14 per cent. of carbon. Solidification commences at *a* and finishes at *b*; from *b* to *c* we have a solid solution of carbon in γ-iron; at *c* ferrite begins to segregate from the solid solution in the form of β-iron; at *d* the iron passes into the α-form, while the solid solution still segregates α-iron, and at the same time becomes richer in carbon. The separation of α-ferrite continues until the point *e* is reached. The system then contains α-iron or α-ferrite, and a solid solution of carbon in iron, or hardenite, with 0·89 per cent. of carbon. The hardenite at *e* passes directly into pearlite.

Let us now follow the changes which take place as a molten solution of iron with 4 per cent. of carbon cools down to ordinary temperatures, forming cast iron with 4 per cent. of carbon.

Region I.—In region *I.* we have a mixture of molten solution and solid martensite with 2 per cent. of carbon.

Region II.—This solidifies into martensite with 2 per cent. of carbon, and graphite on passing into region *II.* There is no cementite formed in this region, because cementite decomposes into iron and graphite at about 1000°.

It is interesting to notice here that the presence of sulphur or manganese retards, while that of silicon stimulates, the separation of graphite.[1] The silicon might act as indicated in the chemical equation[2]—

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[1] H. C. H. Carpenter and B. F. E. Keeling have examined this experimentally (*Journ. Iron and Steel Inst.*, 67. i. 224, 1904).

$$Fe_3C + Si = Fe_3Si + C(\text{graphite})$$

An iron relatively free from silicon, and rich in sulphur or manganese, will have little free graphite; while iron rich in silicon and comparatively poor in sulphur and manganese will be suffused with free graphite. Hence the manufacturer can play silicon and sulphur against one another in order to preserve a uniform percentage of graphite. If the amount of sulphur is great, the amount of silicon should be augmented, and *vice versâ.*

Region III.—As the temperature cools down into region *III.*, the graphite which was produced in regions *I.* and *II.* combines with iron to form cementite, and at the same time the martensite is resolved into cementite and martensite with 0·9 per cent. of carbon, or Arnold's iron subcarbide ($Fe_{24}C$).

Region IV.—As the temperature cools down into region *IV.* the iron subcarbide decomposes into pearlite. The cementite in the final product thus comes both from the decomposition of the martensite and the carbon which is rejected as the molten solution of carbon in iron cools in region *I.*

But the phenomenon of surfusion plays a part. Passive resistance may interfere with the above sequence of changes, and we may get grey, ultra grey, white, or malleable cast iron from the same solution.

i. *Grey Cast Iron.*—Here the sequence of changes is interrupted in region *III.* The transformation of the iron and graphite of region *II.* into cementite is suppressed. The consequence is that the 2 per cent. of graphite which was present in region *II.* is still found in the final product. The cementite of grey cast iron is therefore wholly derived from the decomposition of martensite with 2 per cent. of carbon.

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[1] G. Charpy and L. Grenet, *Metallographist*, 5. 202, 1902; W. J. Keep, *Cast Iron*, New York, 1902.

[2] W. Campbell, *Journ. Iron and Steel Inst.*, 59. i. 211, 1901.

ii. *Ultra Grey Cast Iron.*—Here, owing to the presence of foreign substances, like silicon, the separation of graphite is greatly stimulated; so much so that the martensite passes directly into ferrite and graphite. The final result is a mixture of ferrite and graphite.

iii. *White Cast Iron.*—The formation of the eutectic mixture, martensite and graphite, in region *I.* is suppressed. We have instead a supersaturated solution containing 4 per cent. of carbon dissolved in iron. The martensite so formed passes unchanged into region *II.*; but it is decomposed into cementite and ferrite on passing into region *III.* The final product is, therefore, a mixture of pearlite with cementite in excess. There is practically no free graphite.

iv. *Malleable Cast Iron.*—In malleable castings, white cast iron is heated in a bed of iron oxide, "mill cinder," for five or six days in region *II.* (Fig. 25), so that the graphite which would have separated if the castings had been slowly cooled has time to segregate. The iron oxide removes the graphite near the surface of the casting, thus—

$$\mathrm{Fe_3O_4 + C = 3FeO + CO.}$$

Part of the carbon from within diffuses outwards, and is removed as before. The net result is a casting of grey cast iron with about 0·1 per cent. of combined carbon.

The remaining carbon exists in the form of fine particles of free graphite—Ledebur's temper carbon, in fact. The particles are so small that there is little danger of weakening the casting, as must occur when coarse particles separate, in the ordinary process of manufacture of cast iron. The advantage of malleable castings is that the cost of conversion into steel is avoided, and they are neither so weak nor so brittle as white or grey cast iron.

When the cooling metal is suddenly quenched, various transitional forms are produced, which have received special names—hardenite, martensite, sorbite, troostite, and austenite. Metallurgists are by no means all agreed as to the identification of the different forms; some are denied the right to the name "constituent."

§ 20. Martensite, Hardenite, and Austenite

We have already met with martensite as the solid solution of carbon in iron which separates during the solidification of molten iron. It may contain as much as 2 per cent. of carbon above 1130°; but, as the solution cools, cementite gradually separates out, and the remaining solid solution of carbon becomes poorer and poorer in carbon. The separation of cementite continues until the solid solution has 0·9 per cent. of carbon. This is the eutectic mixture which segregates into pearlite. Some reserve the term martensite for the unsegregated eutectic mixture containing 0·9 per cent. of carbon.[1]

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[1] J. O. Arnold and A. M'William, *Journ. Iron and Steel Inst.*, 55. i. 85, 1899; *Metallographist*, 2. 278, 1899; A. Sauveur, *ibid.*, 2. 305, 1899.

Osmond gives the following relation between the amounts of ferrite and martensite in a steel containing 0·14 per cent. of carbon, and 0·19 per cent. of manganese when quenched at different temperatures.

Quenched at ° C.	Martensite. Per cent.	Ferrite. Per cent.
1340	90	10
1000	61	39
820	46	54
770	24	76
670	14	86

Is the unsegregated eutectic a chemical compound? Arnold thinks that it is a definite compound, and calls it iron subcarbide ($Fe_{24}C$), or hardenite. Others think that we are dealing with a compound of cementite with iron in the form of "iron of crystallization" ($Fe_3C.21Fe$), analogous to the water of crystallization in crystallized sodium carbonate ($Na_2CO_3.10H_2O$), or the "alcohol of crystallization" in $CaCl_2.4CH_3OH$. It is supposed that, below the Ar_1 critical point, the martensite with 0·9 per cent. of carbon dissociates into ferrite and cementite. The term martensite thus includes both the unsegregated eutectic containing 0·9 per cent. of carbon (Arnold) and the solid solution of hardening carbon in iron (Osmond).

Martensite is best formed when a steel containing 0·2 to 0·8 per cent. of carbon is cooled from above the Ar_3 critical point (830°) slowly to the Ar_2 point (730°), and then suddenly quenched in a freezing mixture at −20°. Martensite has the appearance of interlacing needles, shown in Fig. 26, which is a specimen of soft rail steel. Fig. 27 is a specimen of hardened tool

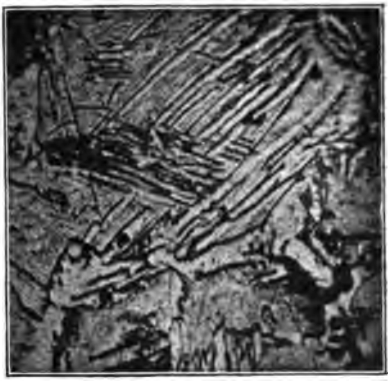

Fig. 26.—Martensite. (E. Heyn.)

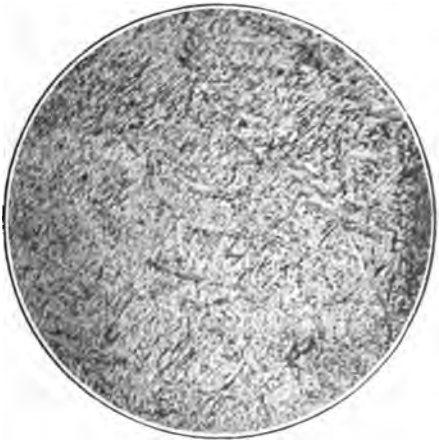

Fig. 27.—Hardenite. (E. Heyn.)

[*To face p.* 40.

steel. It is frequently very difficult, if not impossible, to detect the crystalline structure of martensite in properly hardened steel.

When the steel has just the eutectic proportion of carbon, namely, 0·9 per cent., the martensite is called hardenite, and, by Arnold, iron subcarbide ($Fe_{24}C$); while if there is a greater amount of carbon than this, say 1 to 2 per cent., the result, on quenching, is a mixture of hardenite with a softer constituent, called, by Osmond, austenite, in honour of W. C. Roberts-Austen. Austenite is said to be so soft that it can be scratched with a knitting needle. Some deny the existence of austenite altogether. Fig. 28 shows a specimen of steel containing 1·57 per cent. of carbon, in which barbed plates of hardenite are embedded in a matrix of the alleged austenite.

NOTE.—*To trace the structural changes in the composition of an alloy containing* 4·5 *per cent. of carbon as it cools down from above* 1130°. (Tiemann.[1])

Above 1130° the carbon in excess of 4·3 per cent. separates as graphite. There is 95·5 per cent. of pure iron, and if this has 4·3 per cent. of carbon it will have $4{\cdot}3 \times 95{\cdot}5 \div 100 = 4{\cdot}1$ per cent.

$$\therefore 4{\cdot}5 - 4{\cdot}1 = 0{\cdot}4 \text{ per cent. graphite separates at } 1130^\circ.$$

At 1130°, the eutectic of graphite with martensite containing 2 per cent. of carbon separates. There is 95·5 per cent. of iron, and this has 2 per cent. of carbon; and $2 \times 95{\cdot}5 \div 100 = 1{\cdot}9$,

$$\therefore 4{\cdot}1 - 1{\cdot}9 = 2{\cdot}2 \text{ per cent. graphite separates at } 1130^\circ.$$

Between 1130° and 1000° the percentage of carbon in the martensite diminishes from 2 to 1·8 per cent. Hence, since $1{\cdot}8 \times 95{\cdot}5 \div 100 = 1{\cdot}7$, we have $1{\cdot}9 - 1{\cdot}7 = 0{\cdot}2$ per cent. of carbon.

$$\therefore \text{Total graphite} = 0{\cdot}2 + 2{\cdot}2 + 0{\cdot}4 = 2{\cdot}8 \text{ per cent.}$$
$$\text{Martensite} = 100 - 2{\cdot}8 = 97{\cdot}2 \text{ per cent.}$$

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[1] H. P. Tiemann, *Metallographist*, 4. 313, 1901.

Below 1000° martensite combines with graphite to form cementite:—

Martensite (with 1·8 per cent. of carbon) + graphite = Fe_3C.

Cementite has 6·7 per cent. of carbon, and, therefore, to convert all the ferrite to cementite, we require 6·7 × 95·5 ÷ 100 = 6·4 per cent. of carbon. This would make a total of over 100 per cent. The martensite already has 1·8 per cent. of carbon, and hence, 6·4 − 1·8 = 4·6 per cent. more carbon is needed to convert the 97·2 per cent. of martensite into cementite; but only 2·8 per cent. of graphite are available, hence the 2·8 per cent. of graphite will form 2·8 × 97·2 ÷ 4·6 = 59·2 per cent. of cementite; and 100 − 59·2 = 40·8 per cent. of martensite will remain.

Below 690° the martensite forms pearlite and cementite. Pearlite has 0·9 per cent. of carbon, and cementite 6·7 per cent. Let x denote the percentage of pearlite, and y that of cementite,

$$\therefore x + y = 40{\cdot}8;\ 0{\cdot}9x + 6{\cdot}7y = 1{\cdot}8 \times 40{\cdot}8;$$

hence, $x = 34{\cdot}5$, $y = 5{\cdot}3$. Hence, the total cementite is 59·2 + 6·3 = 65·5 per cent. The percentage amounts of cementite and pearlite can also be calculated by the rule given on p. 29.

§ 21. Sorbite and Troostite

If the temperature at which the pearlite segregates be hastened by quenching the hot metal in lead, the pearlite loses its well-defined lamellar appearance, and we get what is called sorbitic pearlite, or sorbite, after the pioneer worker on the microstructure of steel, H. C. Sorby. Sorbite is unsegregated pearlite, a transitional form between martensite and pearlite. A specimen of sorbitic pearlite magnified 1500 diameters is shown in Fig. 29. The specimen contained 1 per cent. of carbon. Some hold that what we have called granular pearlite, Fig. 20, is really sorbite. Whatever sorbite may be, it is not homogeneous.

There is another transitional form between martensite and pearlite rather difficult to prepare. It is produced when a metal containing about 0·45

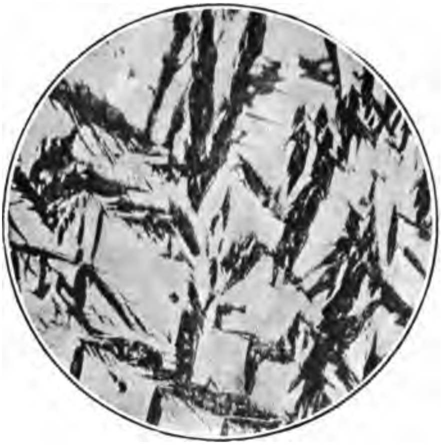

Fig. 28.—Hardenite in Austenite. (F. Osmond.)

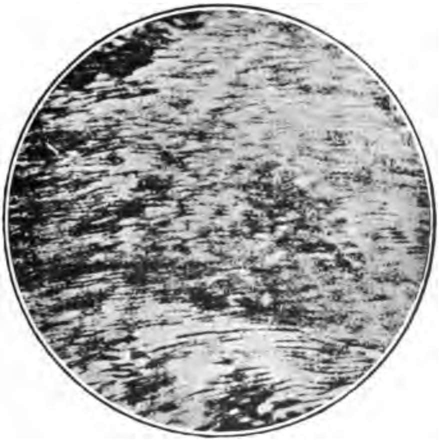

Fig. 29.—Lamellar Sorbite. (F. Osmond.)

[*To face p.* 42.

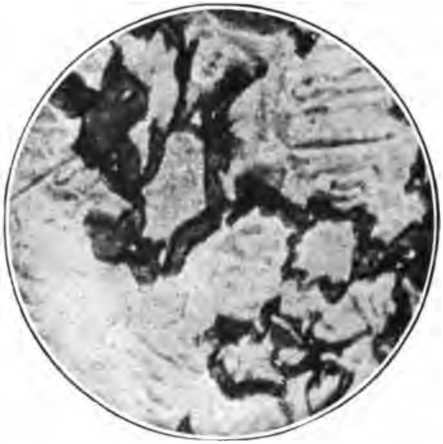

FIG. 30.—Troostite. (F. Osmond.)

[*To face p.* 43.

per cent. of carbon is cooled down to the Ar_1 point (690°) and quenched in water at atmospheric temperature.[1] This constituent is called **troostite**, after a celebrated French chemist, L. Troost. A specimen of troostite embedded in martensite is shown magnified about 1000 times in Fig. 30. The steel contained 0·45 per cent. of carbon.

There are, therefore, two transitional forms between the martensite and pearlite stages of cooling steel.

Martensite → troostite → sorbite → pearlite.

Many metallurgists maintain that troostite and sorbite only refer to particular patterns which the constituents of the cooling alloy assume when the metal is quenched under special conditions. I dare say that it would be possible to get an infinite number of gradations between martensite proper and pearlite. All we can say is that two predominating patterns are called troostite and sorbite.

To prepare troostite, Le Chatelier recommends the heating of a steel bar containing 0·9 per cent. of carbon in a furnace, and leaving the other end free, so that the variation of temperature is uniform throughout the whole length of the bar. After quenching, find the points of medium hardness by means of a file, and, on suitably etching them, the untransformed pearlite will be found separated from the completely transformed pearlite by a zone of troostite.

§ 22. The Phase Rule

The relation between the pressure and volume of a gas confined in a vessel at any fixed temperature is given by the well-known law of Boyle: pressure × volume is constant. If suitable units are chosen, we may write $p \times v = 1$. If the pressure be 0·5 units, the volume must be 2 units. If not, the gas will either expand or contract until the product $p \times v$ is unity. The equation $p \times v = 1$ is called the condition of equilibrium for the gas. There is another relation of a similar nature which enables us to see whether the components of a mixture are those necessary for equilibrium. This condition of equilibrium is called **Gibbs' phase rule.**

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[1] H. C. Boynton, *Journ. Iron and Steel Inst.*, 67. i. 262, 1904.

Before describing the phase rule it will be well to fix special meanings to three terms—component, phase, and degree of freedom.

The **components** of a mixture are those entities which are undecomposable under the conditions of the experiment, and which take part in the reaction. The components of a mixture may either be elements, or "undecomposable" compounds which behave in the given system as if they were elements. The components of an aqueous solution of salt are sodium chloride (NaCl) and water (H_2O); copper and antimony are the components of copper-antimony alloys; iron and carbon are the components of steel.

The components of a system may group themselves in various ways. They may pass from one physical state to another, as when water boils or freezes; they may combine with one another in various ways, as when antimony and copper form copper antimonide (Cu_2Sb); they may form simple solutions, as when salt dissolves in water. Every homogeneous state—solid, liquid, or gaseous; element, compound, or solution—which the components may produce is called a **phase.** The phases of a system are the physical states in which the components exist. A eutectic is not a phase.

If a gas be confined in a vessel, the volume v, temperature T, and pressure p, are related by the condition of equilibrium ($p \times v = 2T$). If only one of these variables is fixed, say the volume, the state of the system will remain undefined, because the vapour may yet retain the fixed volume, while the temperature and pressure have very different values. Two of the three variables must be known before the state of the system can be defined unequivocally. If, say, both the volume and the temperature are fixed, the remaining variable, p, can only assume one definite value. The two fixed variables are said to be arbitrary or **independent variables**; the third, which can be calculated from the equation of equilibrium when the other two are known, is called a **dependent variable.** Another term for independent variable is **degree of freedom.** The above-described system has two degrees of freedom.

A system consisting of liquid water and water vapour can be defined by the two variables pressure and temperature. So long as liquid water is present the pressure of the water vapour is determined solely by its temperature. The state of the system is defined by two variables; one is the dependent variable, the other the independent variable. In other words, the system has one degree of freedom.

If ice, liquid water, and water vapour all exist together none of the three variables can be changed without destroying one of the phases. In consequence the system has no degrees of freedom.

The variability, variance, or degree of freedom of a system is the number of independent variables which must be fixed before the state of the system can be unequivocally defined. The degree of freedom also shows whether a system can survive an arbitrary variation of any one of these three variables without passing into some other condition.

If a system has no degrees of freedom it is said to be invariant; if it has one degree of freedom, univariant; if two degrees of freedom, bivariant; and if the variance of the system be greater than this, multivariant. According to Gibbs' phase rule, a system will be in equilibrium when it has $C - P + 2$ degrees of freedom, where C denotes the number of components, and P the number of phases. If F denotes the number of degrees of freedom of the system, then we may write the phase rule—

$$F = C - P + 2 \quad . \quad . \quad . \quad . \quad (1)$$

If, for instance, a system has two components and four phases, it will have $2 - 4 + 2 = 0$ degrees of freedom, and the system will not be able to survive any variation of temperature, pressure, or in the concentration of its components. A one-component system cannot be in equilibrium if four phases are present, because the system cannot have less than no degrees of freedom.

In the application of the phase rule to alloys it is usual to neglect the vapour pressure, and to consider only two variables, volume or concentration, and temperature. Hence the phase rule assumes the simpler form—

$$F = C - P + 1 \quad . \quad . \quad . \quad . \quad (2)$$

We may now apply the phase rule (2) to a number of examples.

Molten hypoeutectic steel is divariant; the components are iron and carbon; the phase is a molten solution. The same steel solidified at 1300° is also divariant, with the same components, and the phase martensite. At about 720° the phases are martensite and ferrite; hence the system is univariant below 720°. At 690° the system has the phases martensite, ferrite, and cementite; the system is invariant. The pearlite present is not a phase. If the same steel be suddenly cooled from above 690° the phases are also martensite, cementite, ferrite; the system is therefore invariant, neither the temperature nor the concentration of the system can be altered without breaking up the system. As a matter of fact, the system is in an unstable condition. The test for the stability of a system is to find whether the system can survive a small change of temperature. Invariant systems can only be in equilibrium—stable equilibrium—when each variable has one fixed and definite value. There is only one particular temperature, for example, at which the two phases ice and water can exist together in the same system.

System.	Components.	Phases.	Degrees of freedom.
Freezing water .	Water	Liquid, solid	Invariant.
Freezing sodium thiosuphate	Sod. thiosulphate	Liquid, solid	Invariant.
Aqueous sol. of salt.	Water, salt	Solution	Bivariant.
Copper-silver alloy:			
Molten . .	Copper, silver	Solution	Bivariant.
Solid . . .	Copper, silver	Two solids: copper and silver	Univariant.
Freezing eutectic	Copper, silver	Two solids, one liq.	Invariant.
„ selective	Copper, silver	One solid, one liq.	Univariant.
White cast iron .	Iron, carbon	Martensite, cementite, graphite	Invariant.
Grey cast iron .	Iron, carbon	Ferrite, cementite, graphite	Invariant.

Granite is composed of the minerals muscovite ($K_2O . 3Al_2O_3 . 6SiO_2$), quartz (SiO_2), and orthoclase ($K_2O . Al_2O_3 . 6SiO_2$). The components are silica, alumina, and potash; the phases are the three solid minerals; hence the system is univariant, and it is in equilibrium.

A. Findlay's *The Phase Rule and its Applications*, London, 1903, is a text-book devoted to this branch of chemistry.

Exercises.—(1) Find the percentage of pearlite and excess ferrite in medium carbon steels containing 0·3 and 0·7 per cent. of carbon respectively. *Ans.* 33 and 67; and 78 and 22.

(2) An alloy containing a high percentage of graphite is required. If the castings, owing to their thinness, or from the nature of the mould used, are expected to cool rapidly, why should the percentage of silicon be increased? *Ans.* To stimulate the formation of graphite, since rapid cooling retards the separation of graphite.

(3) Trace the changes which steels containing 0·4, 0·8, and 1·6 per cent. of carbon undergo as they cool slowly from the molten condition.

(4) Find the total ferrite, and total cementite in a low carbon steel containing 0·2 per cent. of carbon. *Ans.* 97 and 3.

THE HARDENING, ANNEALING, AND TEMPERING OF STEEL

§ 23. General Properties of Hypo- and Hyper-eutectic Steels

THE mechanical properties of iron-carbon alloys are closely connected with the relative amounts of the two elements. The relation between the percentage of carbon in an alloy and the tenacity in tons per square inch is indicated[1] in the following table:—

Per cent. of carbon =	0·05	0·1	0·2	0·4	0·6	0·8	1·0	1·3
Tenacity . . =	25·00	26·0	31·0	36·0	43·0	58·0	60·0	44·0

The gradual increase in the tenacity of the metal as the amount of carbon approaches the eutectic proportions is brought out very clearly. The results are shown graphically in Fig. 31.

Cementite is a very brittle substance, harder than glass, while ferrite is as soft and as ductile as copper. The relative proportions and the distribution of these two constituents in any alloy must affect its mechanical properties. In hypoeutectic steels the presence of an excess of ferrite renders the metal ductile and tenacious. On the other hand, in hypereutectic steels, the presence of an excess of cementite diminishes the ductility and tenacity of the metal.

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[1] H. M. Howe, *Eng. and Mining Journ.*, 241, 1887.

In a chisel which has to be subjected to blows, there should be no structurally free cementite. Chisel steels, in consequence, contain approximately 0·9 per cent. of carbon. A cutting file which has to withstand but little shock may have a little free cementite—say, 5 per cent. excess cementite—or 1·2 per cent. of carbon; while a razor which has no shock to meet, and wants essentially a keen cutting edge, may have as much as 10 per cent. of excess cementite, or 1·5 per cent. of carbon. The brittleness of such a steel is not a serious objection.

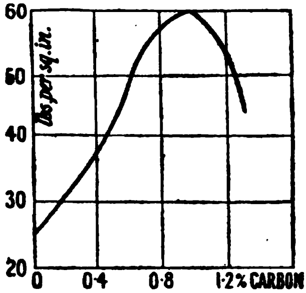

FIG. 31.—Tenacity of Iron-Carbon Alloys.

When the metal has 2 or more per cent. of carbon, the resulting alloys are called cast irons.[2] White cast iron, for example, has so much cementite that it cannot be filed or drilled with ordinary tools. In white cast iron the carbon is principally in the form of cementite. By heating white cast iron to a suitable

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[1] H. M. Howe, *Metallographist*, 4. 177, 1901; 6. 203, 1903; *Encyc. Brit.* 29. 570, 1902.

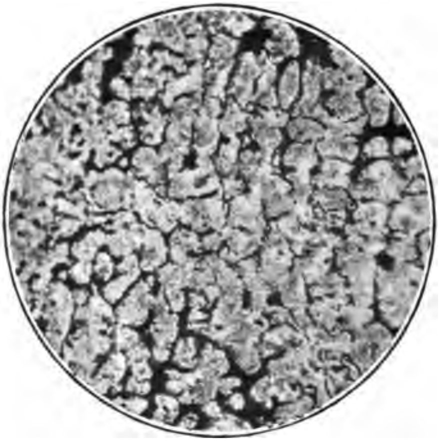

FIG. 32.—White Cast Iron. (F. Popplewell.)

temperature (region *II.*, Fig. 23), the cementite is decomposed into free graphitic carbon. The result is grey cast iron, in which the carbon is not combined with the iron, but is present in the form of graphitic carbon. The effect of free graphite on the properties of the alloy is only mechanical. It destroys the continuity of the metal, and so renders it liable to fracture under the influence of mechanical stresses. Grey cast iron is soft enough to be filed, drilled, and subjected to other mechanical operations. Figs. 32 and 23 represent the microscopic appearance of white and grey cast irons respectively. The dark spots on Fig. 32 consist of pearlite; the lighter portions are cementite.

§ 24. The Influence of Rate of Cooling

The structure and properties of steel and cast iron may be profoundly modified by the rate at which the metal is cooled from a high temperature. Two pieces of steel having exactly the same properties, chemical composition may have entirely different physical properties. The hardness, tenacity, and other properties of the metal depend upon the relative proportions of the allotropic modifications of iron, and of martensite, ferrite, and cementite present in the metal; and these proportions, in turn, depend upon the rate of cooling. There is a particular temperature at which the speed of the transformation of hard martensite into soft pearlite goes on most rapidly; and if the metal be cooled down past this temperature before the hard martensite has time to pass into soft pearlite, then the passive resistance to further change becomes so great that any further change is arrested, and the properties of the hard martensite will predominate. On the other hand, if the metal be cooled down past this critical temperature very slowly, the martensite will pass into pearlite, and the properties of the metal will be altered accordingly. The physical properties of steel thus depend upon—

(1) Its chemical composition; and

(2) The heat treatment to which it has been subjected.

The sole object of hardening, tempering, and annealing steel is to make the metal pass through the various critical temperatures with the proper velocity; in other words, the different transformations which take place at the critical points are arrested when the constituents are distributed in the proportions necessary to confer upon the metal the required degree of hardness. When it is remembered how dependent the rate of cooling of a mass of metal is upon external conditions—specific heat, thermal conductivity, etc., of the quenching fluid—it is easy to see how so many empirical directions for the tempering of steel for special purposes have crept into metallurgical practice. The belief in the efficacy of special nostrums and solutions persists even at this day. But I think that it would be difficult to match the two following receipts for quenching liquids taken from a book of trade secrets published about 1530.[1] In the first you are directed to boil snails in rain water collected in the first two months of the harvest. Red-hot iron quenched in this resulting liquid is said to be as hard as steel. The author suggests the alternative recipe which I give in his own words: "Ye may do the like with the blood of a man of XXX years of age, and of a sanguine complexion, being of a merry nature and pleasant . . . ., distilled in the middst of May."

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[1] W. C. Roberts-Austen, *An Introduction to the Study of Metallurgy*, 147, London, 1902.

In passing, another point may be noticed. For the uniform tempering of a mass of metal it is necessary for the whole mass of metal to undergo the same variations of temperature. This is hardly possible in practice, because the cooling must go on through the outer surface of the metal, but the rate of cooling increases as the *square* of the surface, while the total quantity of heat to be removed increases as the *cube* of the mass of the metal. Hence the rate of cooling diminishes as the size of the specimen increases. A specimen may even be so large that real hardening becomes impossible. The mass cannot be cooled fast enough.

Although the properties of an alloy are closely connected with its chemical composition, yet there is much useful information to be obtained from a microscopic study of the metal which can be obtained in no other way. Knowledge gained by the microscope is not expected to supplant, but rather to supplement the results of the chemical analysis and of the mechanical and physical tests. It is indeed possible that in the near future specifications will be made out for steel with stated amounts of the above-named constituents, sorbite, pearlite, ferrite, etc., when certain specified properties are required. A metal with a large amount of sorbite, for example, is particularly tenacious, and metallurgists have therefore investigated the best heat treatment for retaining a maximum amount of sorbite in the specimen. Hence we have "sorbitic steel rails;" and the so-called "patented wire" alloys, which, by a special treatment,[1] have a large percentage amount of sorbite. The valued wearing qualities of gun-barrels, tires, and armour-plates are enhanced when the sorbite content is high. As an example, Sauveur and Boynton[2] state that a steel with 0·55 per cent. of carbon, cooled from 1150°, has these properties—

How cooled.	Prevailing constituent.	Elastic limit. lbs. per sq. inch.	Tenacity. lbs. per sq. inch.
In furnace .	Pearlite	39,901	81,162
In air. . .	Sorbite	55,000	99,979

§ 25. The Allotropic Modifications of Iron

Besides all this, the relative proportions of the three allotropic modifications of iron (p. 14) play an important part. Gamma iron is said to be as hard as chilled steel, while alpha iron is soft and ductile. The properties of beta iron are not very well known, but they are supposed to be intermediate between the properties of γ- and of α-iron. Let me summarize the probable properties of the three allotropic forms of iron.

Allotropic form.	Normal limits of stability.	Magnetic properties.	Hardness.	Ductility.
Alpha, or α .	680° – 645°	Magnetic	Soft	Ductile.
Beta, or β .	755° – 710°	Non-magnetic	Hard	Brittle.
Gamma, or γ	845° – 800°	Non-magnetic	Hard	Ductile.

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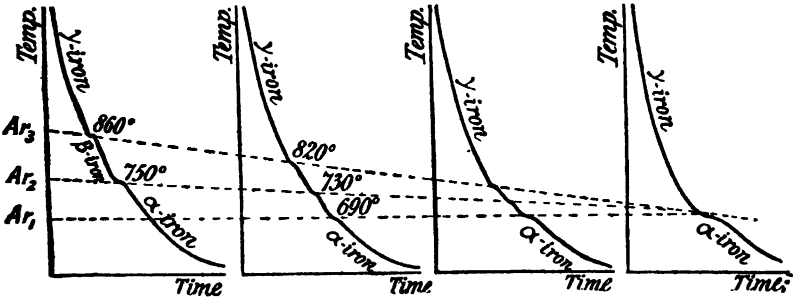
[1] J. E. Stead, *Journ. Iron and Steel Inst.*, **64**. ii. 141, 1903.

[2] A. Sauveur and H. C. Boynton, *Metallographist*, **6**. 148, 1903.

The critical points are very much affected by the presence of foreign substances. The influence of carbon is shown roughly in Fig. 33. The three critical points, Ar_1, Ar_2, Ar_3, gradually converge into one critical point, at about 690°, as the percentage of carbon increases.



Pure Iron *Mild Steel* *Medium Steel* *Hard Steel*

FIG. 33.—The Influence of Carbon on the Critical Points.

The effect of adding carbon is to increase the stability of hard γ-iron. Pure γ-iron is very unstable at ordinary temperatures, and it passes rapidly back to normal α-iron at ordinary temperatures.[1] But if a little carbon be present the rate of transformation is reduced; and if the γ- or α-iron be suddenly cooled the transformation of the hard γ-iron to the soft α-iron goes on very slowly. The rate of transformation is then fastest at 690°, and gradually slows down to zero as the metal cools down to the temperature of the surrounding air.

Still more remarkable effects are produced by alloying the metal with manganese, nickel, chromium, and tungsten. These elements may lower the Ar_1 point from 690° down to atmospheric temperatures or less. In air- or self-hardening steels discovered by R. Mushet the transition temperature is brought down to ordinary atmospheric temperatures by alloying the metal with carbon, tungsten, and manganese. Again, the presence of 35 per cent. of nickel brings down the transition temperature of γ-iron to α-iron as low as 0° C.—the freezing-point of water. A steel of this kind maintains its cutting edge at a much higher temperature than ordinary carbon steel. In the high-speed or rapid-cutting steels[1] these qualities are much enhanced by variations in the composition of the alloy and suitable heat treatment. There are about fifty brands on the market, and all are compounds of iron and carbon with (i.) tungsten and chromium; or (ii.) tungsten, chromium, and molybdenum; or (iii.) molybdenum and chromium.

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[1] H. M. Howe, *Mineral Industry*, 8. 380, 1900; A. Sauveur, *Metallographist*, 1. 27, 1898; H. le Chatelier, *ibid.*, 1. 52, 1898; T. M. Lowry, *Technics*, 1. 450, 1904.

In the non-expansive alloys, or "invar" alloys of iron, containing about 36 per cent. of nickel, discovered by A. E. Guillaume,[2] the transformation of γ-iron to α-iron is just beginning at ordinary temperatures. Now α-iron occupies a greater volume than

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[1] J. M. Gledhill, *Technics*, **1**. 591, 1904; **2**. 17, 1904; J. T. Nicholson, *ibid.*, **1**. 84, 1904.

[2] E. H. Saniter, *Metallographist*, **1**. 251, 1898; G. Gore, *Proc. Roy. Soc.*, **17**. 260, 1869; W. F. Barrett, *Phil. Mag.* [4], **46**. 472, 1873; F. Osmond, *Compt. Rend.*, **128**. 304, 1899; **118**. 532, 1894; Hopkinson, *Proc. Roy. Soc.*, **48**. 1, 442, 1890; H. le Chatelier, *Compt. Rend.*, **110**. 283, 1890; **111**. 454, 1890; A. E. Guillaume, *ibid.*, **124**. 176, 1515, 1897; **125**. 235, 1897; **126**. 738, 1898; *Metallographist*, **6**. 162, 1903; *Nature*, **71**. 134, 1904; *Les Applications des Aciers au Nickel avec un Appendice sur la Théorie des Aciers au Nickel*, Paris, 1904; E. Dumont, *Compt. Rend.*, **126**. 741, 1898; R. A. Hadfield, *Journ. Iron and Steel Inst.*, **64**. ii., 14, 1903.

γ-iron. The transformation from one allotropic form to the other is spread over a certain range of temperature. The normal expansion or contraction of iron, as the temperature rises or falls, is just counterbalanced by the decrease or increase in volume as iron passes from the α- to the γ- condition, or in the reverse direction. Hence it is not necessary to compensate for the effects of temperature in clock pendulums and in geodesic measuring instruments. A similar state of things obtains with the elastic properties of nickel steels, and we are promised nickel steel hair springs for watches, which render it unnecessary to employ compensated balance-wheels.

If ordinary steel be melted with 8 per cent. of manganese and 2·5 per cent. of nickel, the result is a non-magnetic steel.[1] There is no break in the cooling curve. The explanation is that the non-magnetic γ-iron has not passed through its critical points at the ordinary temperatures. A steel with 25 per cent. of nickel does not begin to show magnetization at 0° C., but if cooled in liquid air the transformation of γ-iron to α-iron takes place very quickly, and the iron becomes magnetic.

Magnetization is not a property peculiar to the atoms of the so-called magnetic elements; rather does it seem to be due to a peculiarity in the arrangement of the atoms in the molecule, or of the molecules themselves. If it were possible to make the molecules or atoms of the other elements assume the peculiar arrangement which is the cause of their magnetic properties, then we might make copper, brass, etc., magnetic. This has been done by Heusler.[2] Alloys containing the non-magnetic elements, copper, 60 per cent.; manganese, 26 per cent.; aluminium, 14 per cent., are magnetic—the so-called **Heusler's magnetic alloys.** What is more, if the magnetic iron be combined with Heusler's alloy, the alloy loses its magnetic properties!

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[1] L. Dumas, *Compt. Rend.*, **129**. 42, 1899; *Metallographist*, **3**. 48, 1900; F. Osmond, *ibid.*, **1**. 266, 1898; **2**. 136, 1899; W. F. Barrett and W. Brown, *Technics*, **1**. 123, 1904.

[2] F. Heusler, *Ueber die ferromagnetischen Eigenschaften von Legierungen unmagnetischer Metalle*: Marburg, 1904.

§ 26. Annealing, Tempering, and Hardening of Steel

But let us return to the iron-carbon alloys. When steel is suddenly cooled from above the Ar_3 to the Ar_1 it becomes very hard. A lot depends upon the percentage of carbon. If 1 per cent. of carbon be present, the steel is nearly as hard and as brittle as glass. Low carbon steel is, however, not much affected.

The hardness and brittleness increases with the rapidity of cooling. For example, the cooling of a mild steel containing 0·1 per cent. of carbon furnished the following numbers:[1]—

Cooling agent.	Hardness.
Soda solution (20°) . . .	202
Brine (20°)	156
Cold water (20°) . . .	149
Wood tar (80°)	121
Boiling water (100°) . .	118
Lead (350°)	112

Hardness before quenching = 99.

Still further, it does not matter very much from what temperatures the cooling begins provided it is above the critical range, 720°. This follows from the subjoined tests, due to Arnold,[2] with steel containing

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[1] I. A. Brinell, *Journ. Iron and Steel Inst.*, 59. i. 269, 1901; H. M. Howe, *Iron, Steel and other Alloys*, Boston, 225, 1903.

[2] J. O. Arnold, *Engineering*, 64. 49, 1897; F. Osmond, *Metallographist*, 2. 80, 1899.

0·07 per cent. of carbon. The metal was quenched in brine at 5° C.

Quenched at	Tenacity tons per sq. inch.
918°	31·4
887°	32·6
820°	29·5
780°	29·8
650°	25·6
600°	23·0
525°	22·5
400°	22·0
15°	21·4

The explanation is based upon the fact that the hard martensite has not time to change into the relatively soft pearlite when the steel is suddenly cooled. The rate of change from martensite to pearlite at ordinary temperatures is extremely slow. If steel, quenched at ordinary temperatures, be heated, the changes which were arrested are resumed; and the nearer the steel be heated to 600° the more rapid the change. Steel is annealed or softened when heated for some time at as low a temperature as 230° or 300°.

Steel is tempered at 230° when great hardness is desired[1] and the metal has no shock to meet, as in the case of razors. If the brittleness of this tempering is objectionable, as in the case of chisels and cutting tools which have to withstand certain shocks, such as blows from a hammer, the steel is tempered at a higher temperature, say 300°. But this tempering is at the expense of hardness; the loss of hardness is the price paid to get rid of brittleness.

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[1] P. Longmuir, *Technics*, 1. 333, 1904; 2. 568, 1904; 3. 32, 1905.

The object of annealing is to render the metal tough, soft, or ductile. This is done by diminishing the abnormal qualities the metal acquired through hardening and mechanical working. The metal is annealed by heating it to the Ac_1 critical point, and keeping it at that temperature a sufficient length of time to change the "hardening carbon" to "cement carbon," and the hard into soft allotropic iron. When the effects of hardening have been removed by heating the steel to the Ac_1 point—it is quite immaterial whether the steel be slowly or quickly cooled—the metal will be annealed. In fine—

(1) *Each critical point is accompanied by structural changes, which begin and end with it.*

(2) *No change in the structural composition takes place in a range of temperature where there is no critical point.*

(3) *Sudden cooling serves to fix the structure possessed by steel immediately before cooling.*

§ 27. The Law of Mass Action

Let A denote the state of true equilibrium of steel below the Ac_1 critical point; B the apparent state of equilibrium which is prevented by passive resistance from passing into A. Obviously, A is annealed steel —the state of true equilibrium below the Ac_1 point; B is hardened steel—the state of true equilibrium at a high temperature above Ac_1. If steel be slowly cooled, the successive stages in the transformation from B to A are effected without hindrance; but if steel be quickly cooled, the brake of passive resistance is in full activity before the passage from B to A is completed. Suppose that 10 per cent. of B has passed into A before the brake of passive resistance is sufficiently powerful to prevent any further change, then, if the temperature be raised to 230°, the brake is relaxed, and, say, 10 per cent. more of B passes into A. The remaining 80 per cent. is prevented from passing into A by the passive resistance. Again, by raising the temperature to 300°, the brake will be sufficiently relaxed to allow a little more of B to pass into A; and generally, the higher the temperature, the less the passive resistance. At Ac_1 the brake appears to be sufficiently relaxed to allow the whole of B to pass into A.

This analogy must not be pushed too far. For this reason. If the passage from B into A below the Ar_1 obeys the laws of all chemical changes, then at any fixed temperature the velocity of the transformation of B into A, at any instant, will be proportional to the amount of B remaining to be transformed into A. This is the law of mass action. By "amount" is meant the number of grams of B per unit volume.

Let a denote the amount of B originally present, and x the amount which has already been transformed at any given instant, t; then $a - x$ will denote the amount of B yet remaining to be transformed into A. The law of mass action may now be expressed in symbols, the velocity of the reaction—

$$V = k(a - x),$$

where k is a numerical constant, whose value depends on the conditions of the experiment, the magnitude of the passive resistance, the temperature, etc.

It is easy to see that the velocity of the transformation must slacken down as time goes on. To fix the idea, let k be unity, and the amount of a be 100 grams. At the beginning of the action the velocity will be $V = 100$ grams per hour; but when, say, 10 per cent. has been transformed, V will be 90 grams per hour; when 10 per cent. of B remains untransformed, the velocity of the reaction will be at the rate of 10 grams per hour. When we say that "at 230° the passive resistance is relaxed so that 10 per cent. of B passes into A," the meaning is that when 10 per cent. of B has passed into A the rate of transformation of the remainder of B is too slow to affect the temper very materially when the metal is heated for a short time at the given temperature. It is reasonable to suppose that a more or less prolonged exposure at 100° would anneal hardened steel just as effectually as a shorter exposure at a higher temperature, and that, if the heating at 100° were continued long enough, the whole of B would pass into A.

Those who are familiar with the calculus will see that the velocity of the reaction should be written

$$\frac{dx}{dt} = k(a - x); \text{ or, } x = a(1 - e^{-kt}).$$

When all B has passed into A, we have $a = x$; but this can only happen after the elapse of an indefinite length of time. See J. W. Mellor, *Chemical Statics and Dynamics*, London, 1904.

§ 28. Theories of Annealing and Hardening

The constitution of steel may thus be viewed from two important aspects—

I. The Allotropic Changes of the Iron itself.—The explanation which emphasizes the allotropic changes in the iron is known as the allotropic theory.[1]

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[1] H. M. Howe, *Metallographist*, 1. 150, 1898.

Osmond[1] has dealt particularly with this phase of the work. The hardening of suddenly cooled steel is supposed to be due to the presence of hard γ- or β-iron. This state of things is favoured by the presence of foreign substances, like carbon, nickel, etc. But we do not know if other elements, in the absence of carbon, will effect similar changes in iron. Carbon seems to play an essential part in the action. But other explanations have been suggested.

II. The Relations between Iron and Carbon.—According to the carbon theory,[2] the whole of the facts observed during the hardening of steel can be explained on the assumption that carbon exists in the two states—hardening carbon and cement carbon—already described. The cause of hardening by sudden cooling is due to the retention of carbon in the hardening state. This view does not explain the critical points in the cooling curve of pure iron, and the accompanying changes in, say, the magnetic properties of the metal.

It has also been suggested that the hardening of suddenly cooled steel is due to the presence of hard carbides of γ- or β-iron, which are decomposed at the critical points if the steel be cooled slowly; but, if cooled quickly, passive resistance sets in before the carbides have time to decompose. This is the so-called carbo-allotropic theory of Howe.[3]

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[1] F. Osmond and J. Werth, *Compt. Rend.*, 100. 450, 1885; *Annales des Mines*, [8], 8. 5, 1885; F. Osmond, *ibid.*, [8], 14. 1, 1888; F. Osmond, *Transformations du Fer et du Carbone dans les Fers, les Aciers et Fontes Blanches*: Paris, 1888.

[2] A. Ledebur, *Journ. Iron and Steel Inst.*, 44. ii. 53, 1893; *Stahl und Eisen*, 14. 523, 1894; 17. 302, 436, 1897.

[3] H. le Chatelier, *Metallographist*, 1. 52, 1898.

J. O. Arnold[1] has developed an interesting explanation, which is known as the subcarbide theory. The points of this theory are as follows: In eutectic or saturated steel there is only one critical point, Ar_1, which marks the passage of pearlite into an homogeneous mass corresponding with the empirical formula $Fe_{24}C$. There is no evidence to show that this substance changes at higher temperatures, or that carbon separates from combination with the iron and passes into a solid solution of elementary carbon in iron. On dissolving this material in acid, practically the whole of the carbon is evolved as hydrocarbon gas.

In hypereutectic or supersaturated steel, with, say, 1·4 per cent. of carbon, the pearlite changes into hardenite at about 700°, but the cementite only dissolves in the hardenite above 900°.

With unsaturated steel containing, say, 0·2 per cent. of carbon at the Ar_1, 700°, "the pearlite areas pass into hardenite;" at the Ar_2, 750°, point "the hardenite areas dissolve in the beta ferrite;" at the Ar_3 point "there is a dilation of iron like that of water at 4° C."

The terms "beta" and "gamma" are used in the sense of a range of temperature, and not of allotropic modifications of iron. Arnold lays no stress on the Ar_2 and the Ar_3 points. Tensile tests made on bars of iron containing 0·2 per cent. of carbon, and quenched in iced brine at temperatures ranging from atmospheric up to 1000° in an atmosphere of nitrogen, showed that the tenacity increased from about 500° to 950° proportionally with the quenching temperatures. There was no marked increase in the tenacity at the

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[1] J. O. Arnold, *Journ. Iron and Steel Inst.*, **45**, i. 314, 1894.

Ar_2 or the Ar_3 critical points. The hardening of steel by sudden cooling is supposed to be due to the retention of hard subcarbide.

Let us, then, compare the explanation offered by the allotropic solution theory with Arnold's subcarbide theory for the condition of carbon in cooling iron.

Temperature.	Allotropic theory.	Subcarbide theory.
Above Ar_3 . .	Solid sol. carbon in γ-iron	Sol. of hardenite in iron.
At Ar_3	γ-iron $\rightarrow$ β-iron	Maximum density of sol.
Bet. Ar_3 and Ar_2	Solid sol. carbon in β-iron	Sol. of hardenite in iron.
At Ar_2	β-iron $\rightarrow$ α-iron	Segregation of $Fe_{24}C$.
Bet. Ar_2 and Ar_1	Solid sol. carbon in α-iron	Segregated hardenite.
At Ar_1	$3Fe + C \rightarrow Fe_3C$	$Fe_{24}C \rightarrow Fe_3C + 21Fe$.
Below Ar_1 . .	Ferrite and cementite	Ferrite and cementite.

I have frequently laid stress upon the fact that we can apply the ordinary laws of liquid solutions to the solidified solutions of carbon in iron. This has led to the use of the term "solid solution," as previously mentioned. We are indebted to Roberts-Austen for developing the subject on this side. I have treated the carbo-allotropic theory from the point of view of the theory of solutions, and summarized the results in Fig. 25. It would be an easy matter to reset the diagram so as to summarize Arnold's interpretation of the facts. I do not suppose for one moment that any of these hypotheses is dressed up in its final form. Each one has its weak and its strong points. All are, or ought to be, agreed as to the facts. But metallurgists are yet only groping for the true explanation.

Many attempts have been made to calculate the molecular weight of carbon, or of the carbides dissolved in iron. It is shown in *Elements of Physical Chemistry* that the lowering of the freezing-point of any solution below that of the pure solvent is directly related to the molecular weight of the dissolved substance by formulæ resembling

$$\text{Molecular weight} = \text{constant} \times \frac{\text{weight of substance}}{\text{depression of freezing-point}}$$

On this view, for instance, it is possible to decide whether carbon disulphide dissolved in methyl alcohol is present as CS_2, C_2S_4, C_3S_6, . . . Chemical analysis only shows that the relative proportions of C : S = 12 : 64. So it has been sought whether the carbon is dissolved as C, C_2, C_3, . . ., and whether the carbide is dissolved as Fe_3C, Fe_6C_2, Fe_9C_3, . . . in solutions of carbon in iron. The results cannot be accepted without reservations.[1]

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[1] H. Jüptner von Jonstorff, *Journ. Iron and Steel Inst.*, 55. i. 204, 1899; 57. i. 219, 1900.

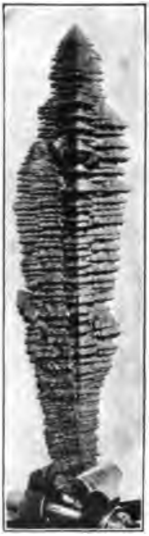

FIG. 34.—Crystal of Ferrite. (D. Tschernoff.)

[*To face p.* 67.

THE CRYSTALLIZATION OF IRON AND STEEL

§ 29. The Crystallization of Iron

WE can all give a more or less crude guess of what is meant by a crystal. The word is generally associated with a definite and regular external form which has been produced spontaneously, and not artificially cut.[1] The octahedral and needle-shaped crystals shown in Figs. 1 and 2 are examples. Then again, in Fig. 34, we have the beautiful crystal of ferrite photographed from a crystal 15 cm. (or 15 inches) long, which Tschernoff found in a cavity of a cast steel ingot. But it is not always so easy to decide whether a substance is, or is not, built up of crystals. In Fig. 35, for example, you see the microscopic appearance of a section from a bar of pure Swedish iron. It is generally supposed that the lines in the diagram represent the surfaces of contact of one crystal with another, and that the crystals have not had sufficient space in which to develop their regular crystalline form. The result is a compact mass of irregular-shaped crystals, called crystalline grains, or simply grains. The metal appears as if it had been built up in the form of a mosaic with irregular-shaped stones. We know that iron is a crystalline substance. Pure iron has been prepared in the form of cubic crystals represented in Fig. 36. But in studying the structure of alloys, the crystals are usually so ill-defined and imperfect that it is impossible to decide from their external shape whether they be true crystals or simply amorphous grains. But we can leave this question with those more particularly interested.

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, 53. i. 145, 1898; *Metallographist*, 1. 289, 1898; F. Osmond, *Annales des Mines*, [9], 17. 110, 1900; *Metallographist*, 3. 181, 275, 1900; with G. Chartaud, *ibid.*, 4. 119, 236, 1901; *Annales des Mines*, [9], 18. 113, 1900; D. Tschernoff, *Metallographist*, 2. 74, 1899.

§ 30. The Development of Crystalline Grains

The junctions of the crystalline grains of pure iron, shown in Fig. 35, and of pure copper, shown in Fig. 37, are typical of pure metals; but when impurities are present the crystals of the pure metal, in the act of crystallizing, reject the impurities which collect at the crystal boundaries. The particles of pure metal slowly migrate and coalesce together, so as to form little islands surrounded by the impurity. Accordingly, in the solidified mass we find the crystals of pure metal enveloped by a film of the metal associated with the foreign substance. This investing membrane separates the crystals of pure metal one from the other. Obviously the mechanical and physical properties of the alloy—tenacity, ductility, elasticity, electrical conductivity—will depend upon the character of the film. The mass of pure metal, for example, may be quite ductile like gold, while the mass of metal with the

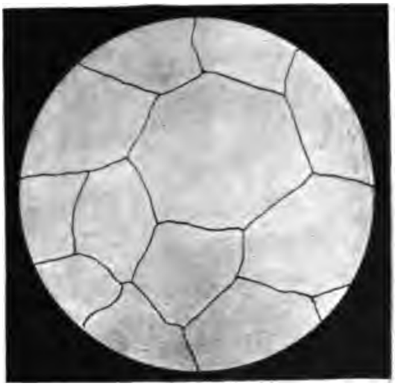

FIG. 35.—Pure Swedish Iron.

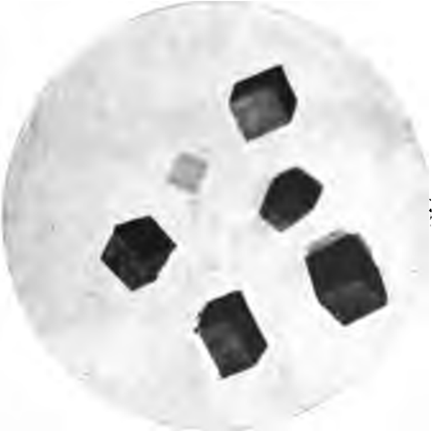

FIG. 36.—Cubic Crystals of Iron. (J. E. Stead.)

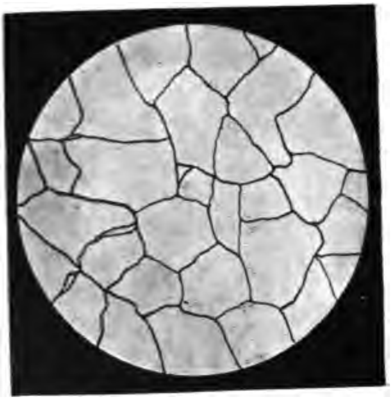

FIG. 37.—Pure Copper. (After J. O. Arnold.)

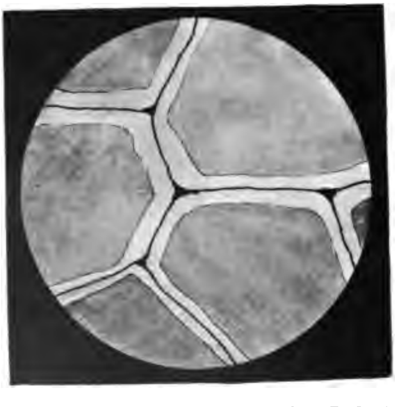

FIG. 38.—Copper-bismuth Alloy. (After J. O. Arnold.)

[*To face p.* 69.

impurity may be quite brittle, as Arnold[1] found to be the case with an alloy of gold with 0·2 per cent. of bismuth; and copper containing 0·5 per cent. of bismuth. A diagrammatic representation of the latter alloy is shown in Fig. 38. The light bands surrounding the grey patches of pure copper consist of an alloy of bismuth and copper, and there is a distinct line of nearly pure bismuth between each band. The individual crystals, when separated from the investing membrane of bismuth and gold, were quite as ductile as gold, while the metal as a whole was as brittle as glass.

Similarly with hypereutectic steels containing an excess of cementite above that required for the formation of pearlite. The pearlite behaves like a pure metal, and rejects the excess of cementite to the boundaries, so as to form a network of cementite in a groundwork of pearlite, as shown in Figs. 39 and 40. The former contains 1·29 per cent. of carbon, the latter 1·8 per cent. In Fig. 40 the enveloping walls of cementite are much thicker than in Fig. 39, as you would expect from the percentage composition of carbon. The reason the network of cementite is light in Fig. 39 and dark in Fig. 40 is due to the fact that the illumination is direct in the former case, oblique in the latter. The whiteness or blackness of the lines depends upon the mode of illumination when the photograph was made.

Sometimes the heavier constituents of the cooling alloy settle at the bottom, and the lighter near the top. Ice, for example, rises to the surface of freezing water, and graphite collects in the form of beautiful plates—known as "kish"—at the surface of cooling ultra-grey cast iron.

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[1] J. O. Arnold and J. Jefferson, *Engineering*, 61. 177, 1896; T. Andrews, *ibid.*, 66. 411, 541, 733, 1898; *Metallographist*, 2. 105, 1899; W. G. McMillan and R. H. Housman, *Nature*, 54. 171, 1896; F. Osmond and W. C. Roberts-Austen, *Phil. Trans.*, 187. 423, 1896.

§ 31. Grain Size and Fracture

The fracture of a metal, or the broken surface which the metal presents, may be fibrous or crystalline. Experts can deduce a good bit of information from the appearance presented by, say, a fractured pig of cast iron. Each variety of steel has its own peculiar fracture. Wrought iron has a fibrous fracture, while high carbon steel has a characteristic porcelain-like fracture.

The same piece of metal, however, may be broken so as to present very different fractures. Wrought iron, for example, if nicked on one side and gradually bent, gives a well-defined fibrous fracture; while, if nicked on all four sides and suddenly broken, the fracture will be crystalline. But these are well-known "tricks of the trade."

The fracture, when performed under definite conditions, furnishes a true indication of the coarseness of the crystallization. The degree of coarseness of the fracture, or the average size of the crystalline grains when a suitably prepared specimen is examined under the microscope, is called the grain size of the specimen.

As a general rule, the smaller the grain size the better the steel, and we naturally ask: Is there any relation between the grain size and the highest temperature to which the steel has been heated in annealing?

For practical purposes the physical properties of steel may be taken to depend upon—

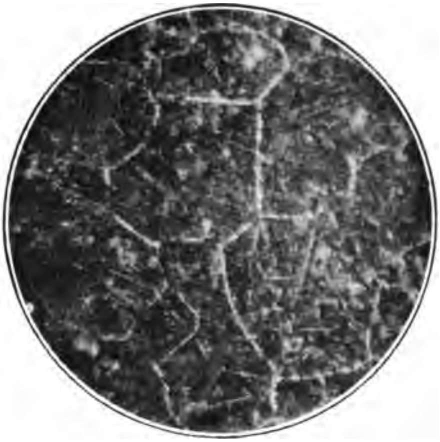

Fig. 39.—Iron with 1·3 per cent. Carbon. (F. Popplewell.)

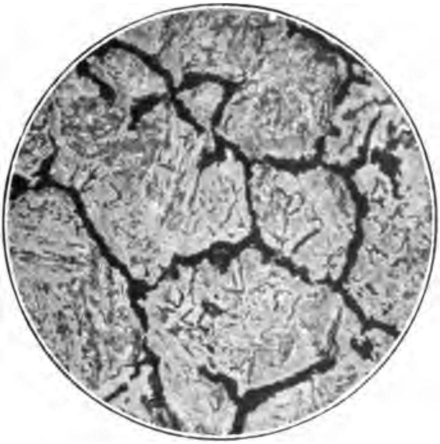

Fig. 40.—Iron with 1·8 per cent. Carbon. (F. Popplewell.)

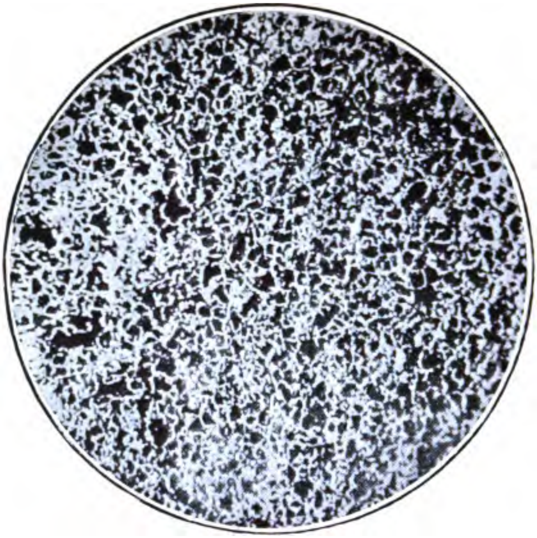

FIG. 41.—Grain Size acquired at 900°. (*The Iron Age.*)

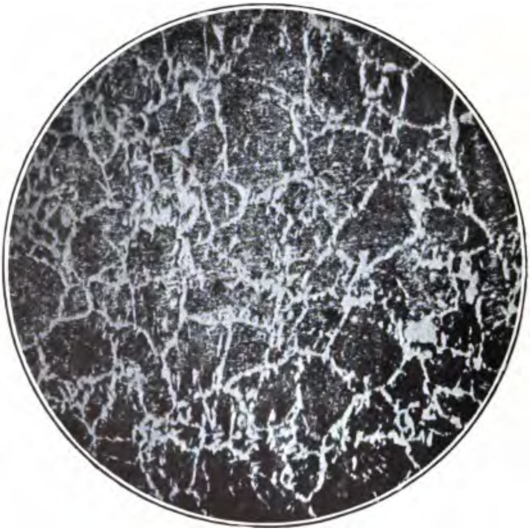

FIG. 42.—Grain Size acquired at 1200°. (*The Iron Age.*)

[*To face p.* 71.

(1) Chemical composition, *i.e.*, the relative amounts of other elements present;

(2) Distribution of constituents, *i.e.*, the relative proportions of ferrite, cementite, etc., present;

(3) Size of grains.

Here are a few tests, by Sauveur, on the relation between the size of the grain and the physical properties of the same piece of steel:[1]—

Size of grain in 0·0001 sq. mm.	Tensile strength kilogrm. per sq. mm.	Elongation per cent. of length.	Reduction per cent.
148	69·6	15·0	20
118	70·3	19·0	22
62	77·7	22·5	35

The relation between the average area and the tenacity is—

$$\text{Tenacity} = 75{\cdot}5 - 0{\cdot}004\,A.$$

An experienced man can generally give a surprisingly accurate guess of the temperature to which the steel has been heated, from the fracture, or from the microstructure of the metal. Tschernoff and Brinell have observed that the higher the temperature of annealing the larger the size of the grain. This will be evident on examination of Campbell's diagrams, Figs. 41 to 43, which represent the appearance of soft steel when heated to the temperatures indicated: Fig. 41 to about 900°; Fig. 42 to 1200°; and Fig. 43 to about 1300°. A similar result has been observed during the crystallization of brass.[1] The following are the more important generalizations which have been made:—

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[1] N. Ljamin, *Chem. Zeit.*, **21.** 205, 1899; *Baumaterialien*, **3.** 105, 1899, finds the tenacity in different steels varies directly as the size of the pearlite grains—at the same finishing temperature; H. Jüptner von Jonstorff, *Metallographist*, **2.** 222, 1899; *Stahl und Eisen*, **19.** 237, 278, 1899; F. Osmond, *Annales des Mines*, [9], **8.** 153, 1900.

I. The higher the temperature above the Ac_1 *point from which steel cools the larger the size of the grains, while if the* Ac_1 *point is the highest temperature attained, then the steel will have the finest possible structure which it can assume.* Howe and Sauveur[2] seem to believe that there is a definite relation between the size of the grain and the highest temperature to which the steel has been heated. For a steel containing 1·1 per cent. of carbon, this relation can be represented by the formula—

$$T = 680 + 281{,}250\,A$$

where A denotes the actual area of the grain in square millimetres; T is the highest temperature reached in the annealing furnace. Tschernoff's experiments do not quite tally with this formula at the more elevated temperatures, say 1400°, although at lower temperatures the agreement is satisfactory. The more exact law is given by the curve in Fig. 44. Let us illustrate

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[1] A. H. Coote, *Technics*, **2**. 290, 1904; H. M. Howe, *Iron, Steel, and other Alloys*, Boston, 250, 1904.

[2] H. M. Howe and A. Sauveur, *Eng. and Mining Journ.*, **60**. 537, 1895; A. Sauveur, *Trans. Amer. Inst. Mining Eng.*, **26**. 863, 1896; *Metallographist*, **2**. 264, 1899; H. Jüptner von Jonstorff, *Stahl und Eisen*, **19**. 237, 278, 1899; I. A. Brinell, *Journ. Iron and Steel Inst.*, **29**. i. 365, 1886; *Metallographist*, **2**. 129, 1899; H. Fay and S. Badlam, *ibid.*, **4**. 31, 1901; J. E. Stead, *Journ. Iron and Steel Inst.*, **53**. i. 145, 1898; **54**. ii. 147, 1898; *Metallographist*, 1. 289, 1898; **2**. 85, 1899; C. H. Risdale, *ibid.*, **3**. 64, 1900; *Journ. Iron and Steel Inst.*, **53**. i. 220, 1898; **56**. ii. 102, 1899; E. J. Ball, *ibid.*, **37**. i. 85, 1890; **39**. i. 103, 1891; J. O. Arnold, *Proc. Inst. Civil Eng.*, i. 123, 1895; D. Tschernoff, *Proc. Inst. Mech. Eng.*, 152, 286, 1880.

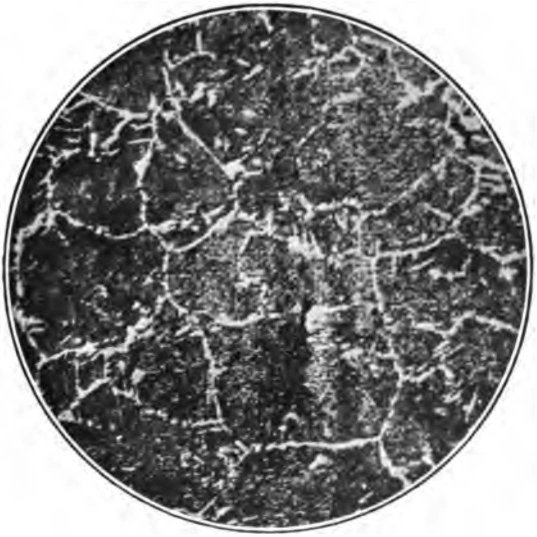

FIG. 43.—Grain Size acquired at 1300°. (*The Iron Age.*)

[*To face p.* 72.

its application to the specimen of steel for which the curve Ac_1P was determined; SP, that is OM, represents the size of the grain at the temperature OS.

If the size of the grain is smaller than it should be at any given temperature, then the grain will grow in size until it reaches the normal size indicated by the above law. On the other hand, if the grain is larger than that which is characteristic of any particular temperature, the grain will *not* shrink to its normal size. For example, if the steel has the grain size SP, Fig. 44, at the temperature OR, the size of the grain will remain OM, and will not shrink to ON. The slope of the curve will be different for different steels; the steel represented in Fig. 44 contained 1·1 per cent. of carbon, and traces of silicon and manganese.

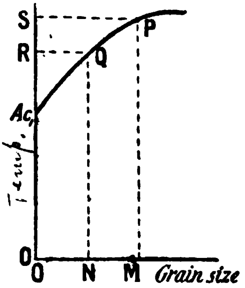

Fig. 44.

The average maximum size of the grain at any temperature is the average size of the grain when the full sectional area is presented. In some places only part, or one corner of the grain is shown. Sauveur[1] uses the camera lucida planimeter for measuring the size of the grains. Risdale recommends a comparison of photographs made on the same scale. Morse counts the number of grains in a measured area on the photograph, and takes the average of as many different grains as possible. This is reduced to actual size on dividing by the magnification and the number of grains counted.

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[1] A. Sauveur, *Trans. Amer. Inst. Mining Eng.*, **22**. 546, 1893; *Journ. Iron and Steel Inst.*, **56**. ii. 195, 1899; *Metallographist*, **2**. 264, 1899; R. G. Morse, *ibid.*, **3**. 130, 1900; *Trans. Amer. Inst. Mining Eng.*, 29, 1900.

II. If hardened or unhardened steel be heated to the Ac_1 *critical point, all previous crystalline structure, however coarse and distorted, is obliterated and replaced by the finest possible structure which the metal can assume.* This rearrangement of the size of the grains is called heat refining. The breaking up of the old structure is due to the change of cement into hardening carbon, or of cementite to martensite, and to the diffusion of the carbon after these changes. The transformation of cement to hardening carbon is sudden; while the passage from hardening to cement carbon takes place gradually, and is accompanied by the evolution of heat.[1]

The law only applies to hard steels. With hypoeutectic steels, the old coarseness is not quite obliterated when the Ac_3 point is reached; and as the old structure being destroyed between the Ac_1 and the Ac_3 points, a new growth sets in. Consequently, hypoeutectic steels cannot be refined so completely as eutectic, or hypereutectic steels, because the old structure cannot be effaced without permitting, at the same time, a considerable growth of the new.

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, **53**. i. 145, 1898; **54**. ii. 137, 1898; *Metallographist*, **1**. 289, 1898; I. A. Brinell, *ibid.*, **2**. 129, 1899.

Stead[1] has shown that with very soft steels, containing 0·25 per cent. to 0·12 per cent. of carbon, the ferrite grains grow larger as the temperature rises above 500°, and, instead of being refined, the grains continue growing as the temperature passes the Ac_1 (700°) point, and continue growing until the Ac_2 point is reached. No material increase in size then occurs until the Ac_3 (900°) point is reached, when the former granular structure is broken up, and the steel is refined. This shows how necessary it is to avoid heating soft steels for any length of time at a dull red (about 500°).

III. If steel be heated for some time to a temperature just above 1000°, *the metal, even mild steel, becomes very brittle, and acquires a coarse crystalline structure.* The size of the crystals may be considerably reduced by quickly cooling the steel from the temperature of overheating although the brittleness still persists. Steel so affected is said to be **overheated.** The disease can be cured by heating the steel for a few days near the Ac_3 (850°–900°) critical point.[2]

There is an aggravated form of overheating produced when the metal is heated to a temperature so near its melting-point that an evolution of gas occurs. This gas forces the crystalline grains apart, and so destroys the continuity of the mass. The gases are probably carbon monoxide, formed by the union of the occluded oxygen with the carbon of the steel, as well as hydrogen and nitrogen. The disease is called burning, and the steel is said to be burnt. Burnt steel is brittle both hot and cold; it has a coarse crystalline fracture, and a coating of oxide is frequently found on the faces of the crystals at the fractured surface.

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, 53. i. 289, 1898.

[2] E. Heyn, *Journ. Iron and Steel Inst.*, 62. ii. 73, 1902; W. Campbell, *ibid.*, 64. ii. 359, 1903.

The cooling curve of pure iron shows critical points at about 400°. The effects are due to the hydrogen occluded in the metal.[1] It is interesting to notice that the presence of hydrogen gas diminishes the ductility of the metal, as you can see by dipping two pieces of steel wire in dilute sulphuric acid (one of acid to ten of water by weight) for half an hour, and keeping a third piece for comparison. The pickled wires are quite brittle. One of the pickled wires may be heated to 100° to show that when the hydrogen gas is driven off by heating, the metal regains its ductility.

Burning is an incurable disease—at least so far as heat treatment is concerned. Heat treatment can only induce allotropic or chemical changes in the alloy; it cannot close up actual fissures in the metal. Mechanical kneading and compression by hammering and rolling is much more effective in closing up the cracks, especially if the oxidation is not very great.

Why do not ingots and castings burn as they pass through the burning range on cooling down from the casting temperature, whereas if a steel bar be heated to this temperature and then cooled—quickly or slowly—it is incurably burnt? We have seen that burning is caused by the oxidation of the crystal faces by the inward diffusion of oxygen. When a casting is cooling, the hydrogen dissolved by the metal is working outwards in such a way as to prevent the entry of oxygen; but steel bars made from these ingots, having lost their hydrogen, have nothing to prevent the infiltration of atmospheric oxygen between the faces of the crystals.

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[1] E. Heyn, *Eisen und Stahl*, **20**. 837, 1900; *Metallographist*, **6**. 39, 1903; L. Romanoff, *ibid.*, **2**. 247, 1899; *Stahl und Eisen*, **19**. 265, 1899: for oxygen in steel.

§ 32. Influence of Mechanical Work

The normal crystallization of steel generally leaves the metal in a state not well adapted for industrial requirements. But this structure may be broken up by the mechanical work of rolling and hammering the metal. The forging may be performed under two conditions:—

i. *Hot work* when the metal is forged above the critical temperature Ac_1.

ii. *Cold work* when the forging is performed below the Ar_1 critical point. If the temperature is rising from below the Ar_1 point, then at temperatures between the Ar_1 and the Ac_1 points, the metal is being cold worked; and hot worked if the temperature is falling from above the Ac_1 point.

The following are the more important structural changes which take place during the mechanical working of the metal:—

I. If the work is sufficiently vigorous to affect all parts of the mass, no crystallization takes place while the steel is being worked.[1]

II. Hot work has no direct action upon the structure of the steel, but, as it retards crystallization till a lower temperature is reached, it may influence structure in this way. Howe[2] explains the relation between the temperature of the hot work and the size of the grain, somewhat as follows: If the steel is worked at a temperature *OB* (Fig. 45), the rollers break down the grain; after that, the crystalline grains grow along the line *BC* as the metal cools down. If the cooling mass be again rolled, the grain will be again broken up, and the size of the grain on subsequent cooling will be reduced to *RE*. The grain goes on growing as the metal cools along the line *EF*, only to be again broken up when the metal is rolled again. This alternation of changes goes on as the steel passes through and through the rollers. The result is the zig-zag *BCEF* . . . *HIJ*. If the rolling ceases when the curve *HI* crosses the normal line *OA*, the size of the grain in the finished product will be *OJ*. Hence, *the size of the grain will be smaller the lower the finishing temperature.* The finishing temperature is the last effective rolling or hammering.

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[1] R. Job, *Metallographist*, 5. 177, 1902; S. S. Martin, *ibid.*, 5. 191, 1902; A. Sauveur, *ibid.*, 5. 197, 1902.

[2] H. M. Howe, *Iron, Steel, and other Alloys*, Boston, 263, 1903.

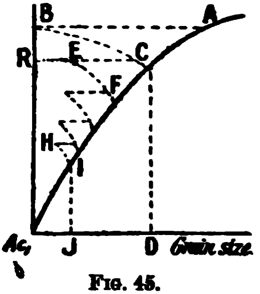

FIG. 45.

The object of rolling is to expel slag; close up the blowholes and other irregularities. The metal will be softer the hotter it is, and less power will then be required to do the work. Hence it it is desirable to work the metal as hot as possible. But we must set against this the facts just brought under notice—

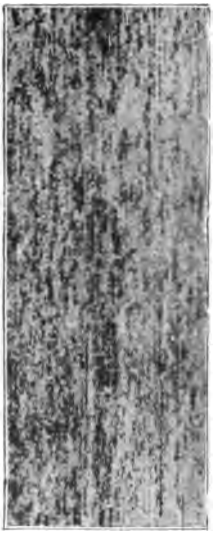

FIG. 46. (J. E. Stead.)

FIG. 47. (J. E. Stead.)

[*To face p.* **79.**

the higher the finishing temperature the coarser the grain, and the more brittle the metal. Hence the higher the finishing temperature above the Ac_1 point the poorer the quality of the steel. The practical application will be obvious. Work the metal at as high a temperature as possible, so as to save power during rolling, and then reduce the temperature by, say, a current of cold water, so that the rolling may take place at a low temperature. This is done, for instance, in tire and rail rolling. In welding, too, after the two pieces are actually joined, the smith continues hammering until the temperature has fallen low enough to insure a relatively fine grain in the finished piece. The parts to be welded are first thickened, so as to allow of this "hammer" refining.

III. Cold work distorts the grain, or flattens and elongates the crystals in the direction of rolling. The lower the temperature the more pronounced the effects of cold working. The structural changes of cold working can be obliterated by heat treatment up to or over the Ac_1 critical point. The adjoining diagrams (Figs. 46 and 47) show a specimen of rolled steel before and after annealing. Notice the fibrous structure of the sheet (Fig. 46) after rolling at 600°, and the crystalline structure of the same sheet after annealing (Fig. 47). The fractured surface of the rolled sheet had a fibrous appearance, and the sheet was not brittle; the second broke with a crystalline fracture after severe punishment.

§ 33. Influence of Other Elements

A large number of empirical observations with the testing machine have been made upon the influence of elements like manganese, sulphur, silica, chromium, nickel, and phosphorus upon the properties of the iron-carbon alloys. A full description of their effects must be sought in the regular text-books.[1] Some elements increase, others diminish the tenacity.

I. The tenacity is lowered by elements like silicon, phosphorus, and sulphur, which promote the formation of graphitic carbon or cementite; by elements like phosphorus and copper, which cause the formation of other separations; by elements which increase the size of the grain, *e.g.* phosphorus and manganese; by non-metallic elements which induce the formation of thick cell-walls, or which separate the crystalline grains one from the other; for instance, gases, large amounts of silicon, compounds of iron and sulphur, and of manganese, and sulphur, slag, and oxides.

II. The tenacity is increased by elements like nickel and cobalt, which possess a high tenacity; by small amounts of elements like manganese, chromium, tungsten, titanium, which hinder the separation of graphitic carbon; by small amounts of elements like silicon and aluminium, which hinder the formation of blow-holes; and by elements like nickel and chromium, which favour the formation of firmly locked crystals.

The internal changes by which these effects are produced are little understood. The "impurities" or "foreign substances" may not only react upon the iron, but also upon the carbon, and upon each other. Among the secondary reactions we have the possible formation of manganese carbides—Mn_3C; $Fe_3C.4Mn_3C$—when manganese is present; with chromium we may have the double carbide—$3Fe_3C.Cr_3C_2$; if silicon be present along with manganese we may have manganese silicide, MnSi, produced; and with sulphur, manganese sulphide, MnS; while phosphorus may produce many varieties of phosphides of iron.[1]

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[1] A. H. Hiorns, *Steel and Iron*, London, 1903; or, F. W. Harbord, *The Metallurgy of Steel*, London, 1903; A. Carnot and E. Goutal, *Annales des Mines*, [9], **18**. 263, 1900; *Metallographist*, **4**. 286, 1901; H. Jüptner von Jonstorff, *ibid.*, **2**. 222, 1899; *Stahl und Eisen*, **20**, 939, 1899; T. Turner, *The Metallurgy of Iron*, London, 1904.

Besides the formation of compounds of this type, there is also the possible existence of allotropic forms of the foreign elements—nickel, cobalt, say—which modify the properties of the alloy in a specific manner. There is thus a vast field of work before the metallurgist. What is the effect of the various secondary components upon the physical properties of the final product? Under what conditions are they formed? How can the formation of deleterious secondary products be hindered?

EXERCISES.—(1) Why should the finishing temperature of unhardened steel be at the Ac_1 critical point? *Ans.* The smaller the grain the more ductile and tough the metal, etc.

(2) How can the structural deformation brought about by cold work be obliterated?

(3) Why have the central portions of thick pieces larger crystalline grains than the outer portions? *Ans.* In practice, thick pieces cannot be finished at a uniform temperature. The central portions of thick pieces leave the rollers at a higher temperature than the outer layers, etc.

(4) If chisel steel which has been tempered at 300° be heated to 230°, what changes will take place in the temper of the metal? *Ans.* None, if the brake of passive resistance had relaxed to its limit at 300°. But see § 27.

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, 58. ii. 60, 1900; *Metallographist*, 4. 89, 199, 332, 1901.

THE INFLUENCE OF STRESS AND STRAIN

§ 34. Intercrystalline or Intergranular Weakness

THE popular idea of the qualities of steel has crystallized into the phrase "as true as steel," but metallurgists have now to face the uncomfortable fact that steel which has safely passed all the mechanical tests occasionally develops an extraordinary tendency to become brittle, and breaks under stresses far below the elastic limit of the metal. The condition of purchasing steel rails is that they stand without fracture the blow of a ton weight falling 30 feet. But the director of one of the largest railways in England, the late Sir Lowthian Bell, has said that "occasionally rails for no apparent reason break with a blow from the height of a half or a quarter of that; and sometimes after rails have been in use for a short time they positively break in two with a fall of less than one foot." I am also informed that the United States Government have gone back to wrought iron anchors for their ironclads, on account of the treacherous and mysterious fractures which occur with approved types of cast steel kedge anchors.[1] It is therefore of interest to examine this question in a little more detail.[2]

Just as the shaking of a superfused solution of sodium thiosulphate might induce the crystallization of the substance, so is it conceivable that, if the constituents of steel were in an unstable state of equilibrium, a sudden shock, or the continued recurrence of a series of vibrations, might so relax the passive resistance that the internal structure would be modified in some way, and brittleness result.

The disease may not be due to any alteration in the crystalline form of the metal. Steel is normally in a crystalline state. In many cases the source of weakness is the joints between the crystalline grains. When such a metal is fractured the line of fracture follows the junction of the grains. Stead calls this ailment intergranular or intercrystalline weakness (*inter* = between). We have had examples. Arnold's work on the influence of bismuth on copper and on gold. One per cent. of sulphur arranged as a mesh of iron sulphide will entirely destroy the ductility of the iron, reducing the ultimate stress from 20 to 2 tons per square inch. Sulphide of iron is only found in appreciable quantities in iron low in manganese. "Manganese," says Arnold, "seems almost entirely to prevent the formation of cell walls of iron sulphide."[3]

The network of cementite which envelops the crystal grains of steel containing over 1 per cent. of carbon are the principal lines of weakness. The metal, when fractured, generally breaks through the centre of this brittle envelope. The coefficient of contraction of the cementite cell walls is greater than of the cell contents. Pearlite cells, for example, bound together by thick cementite walls (Fig. 40), are liable to rupture, because the coefficient of contraction of the cementite cell walls is greater than the cell contents. The mass is, in consequence, very feebly held together, and a sudden blow will easily fracture the metal.[1] Intergranular weakness resembles the weakness of a brick building with faulty mortar; the whole might collapse, as jerry-built houses sometimes do when put to a severe test.

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[1] W. M. Carr, *Metallographist*, 5. 58, 1902.

[2] We shall not consider weakness due to the presence of blowholes or slag. See C. H. Risdale, *Journ. Iron and Steel Inst.*, 64. ii. 232, 1903.

[3] J. O. Arnold and G. B. Waterhouse, *Metallographist*, 6. 302, 1903; *Journ. Iron and Steel Inst.*, 63. i. 136, 1903.

There is another type of intergranular weakness which is due to imperfect union of the crystal grains. This is particularly marked in phosphorous steels. The crystal grains, on cooling, contract unequally, and tend either to draw the grains away from each other, or to leave the mass in a state of unnatural tension. The fracture then follows the granular junctions. Thick plates and bars are frequently brittle, because comparatively little work has been done on them. The crystals are not interlocked one with another as in steel which has been well worked.

Intergranular weakness may, therefore, be of two kinds—

(1) Brittle envelope surrounding the crystal grains.

(2) Imperfect union of the crystal grains.

Intergranular weakness may often be detected under the microscope. Steels which exhibit "loose" intercrystalline ferrite joints,[1] or a meshed or cellular structure of any kind, are to be labelled "dangerous."

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[1] J. O. Arnold, *Metallographist*, 5. 267, 1902.

§ 35. Intracrystalline or Cleavage Weakness

Stead has pointed out another type of weakness in sheet steels which has to do with the crystals themselves without reference to the union of one crystal with another. It is a kind of intracrystalline weakness (*intra* = within). It is characteristic of some crystals to break more readily in some directions than in others. For example, in a cubical crystal, say of

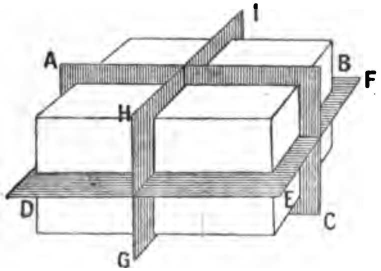

Fig. 48.—Cleavage Planes.

DEF, *GHI*). Iron crystallizes in the cubic system, rock salt, the crystal splits up more readily in the three directions *ABC*, *DEF*, *GHI* (Fig. 48), parallel to the three crystal faces, and at right angles to one another. This property of crystals is called cleavage. The directions in which the crystal splits are called cleavage planes. A cubical crystal of rock salt has the three cleavage planes shown in Fig. 48 (*ABC*, and therefore every separate grain in a crystalline mass of iron is more liable to split up in these three directions than in any other.

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[1] That is, a junction which develops rapidly on slight etching with nitric acid, as indicated on p. 100.

If a bar of iron could be cut from a single crystal, that bar would have three lines of weakness in the direction of the three cleavage planes; while if the bar were built up of a number of crystals whose cleavage planes were all in the same direction, that bar would be more readily broken in the direction of its cleavage planes, neglecting for the moment inter-granular weaknesses. Still further, if a number of adjacent crystals at one particular spot in a bar of iron were built up in this manner, then the bar would be more liable to rupture along the cleavage planes at this spot when subjected to the influence of a properly directed force. On the other hand, if the cleavage planes of the adjacent crystals are inclined at considerable angles to one another, the bar would be less liable to break than one in which the crystals were arranged symmetrically. Figs. 49 and 50 will make this clear. The dotted lines, *ab*, Fig. 49, represent the

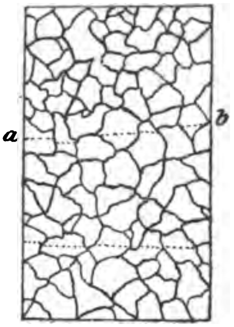

FIG. 49.

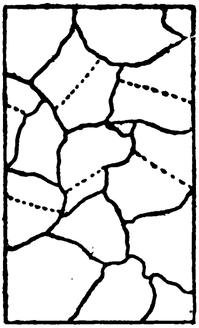

FIG. 50.

cleavage planes across a sheet of iron when the crystals are arranged symmetrically; while in Fig. 50 the crystals are arranged in an irregular manner. The cleavage plane of Fig. 49 run along parallel lines, and the sheet would therefore be more liable to rupture than the sheet shown in Fig. 50, where the lines of weakness are not in the same direction, and this in spite of the fact that Fig. 49 has a finer grain.

Other things being equal, a fine-grained structure is stronger and tougher than a coarse-grained piece. Figs. 49 and 50 show that this order of things may be reversed. Fortunately the crystals of iron and steel do not in general grow symmetrically. But the development of small into larger grains in the annealing ovens shows that the cleavage planes of a number of adjacent crystals may assume the same direction. Wherever there are large crystals there must be large cleavage planes, or lines of weakness.

Intercrystalline or cleavage weakness of this kind is comparatively rare, and its presence may be detected by the usual mechanical tests.

A remarkable fact connected with the brittleness of soft steel is, that the fracture is nearly always at an angle of 45° to the direction of rolling,[1] and at right angles to the surface of the steel. But this is also the orientation of the crystals of the metal made brittle by annealing. So long as this material is bent at right angles to that direction, there is no danger of breaking, but if the bending is attempted at an angle of 45° to the direction in which the plates were rolled fracture takes place. The rolling seems to impart a tendency to crystallization in certain fixed directions which develop during annealing.

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, **54.** ii. 137, 1898.

§ 36. Birth, Growth, and Structure of Crystals

It is a fascinating and wonderful power which causes substances in passing from the liquid to the solid state to assume definite and characteristic shapes. I dare not say much upon the birth and growth of crystals. The first visible sign of crystallization in a fluid is the appearance of a globular nucleus, called a globulite,[1] about which the integral parts of the crystal are deposited in a regular manner, so as to produce a typical crystal. The series of drawings shown in Fig. 51 are adapted from a set of "cinematographic" photographs of a growing crystal of potassium iodide under a magnification of 100 diameters, and exposed 0·25th of a second.[2]

The little crystal at the bottom right-hand corner of 2, Fig. 51, has a globular form, characteristic of the primitive "globulite." The globular shape, however, is really due to the fact that, while the crystal is small, its growth is so rapid that the borders of the growing mass does not seem to possess a sharply defined outline.

Every true crystal is made up of smaller crystals, each of which is a perfect replica of the original. These crystals are made up of smaller crystals, and these in turn, made up of still smaller crystals, and so on. The small crystals—called crystallites—are arranged in a perfectly definite and regular manner.

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[1] A. Fock, *An Introduction to Chemical Crystallography*, Oxford, 1895; J. W. Judd, *Nature*, **44**. 83, 1891; G. D. Liveing, *ibid.*, **44**. 156, 1891.

[2] T. H. Richards and E. H. Archibald, *Phil. Mag.*, [6], **2**. 488, 1901; *Amer. Chem. Journ.*, **26**. 61, 1901.

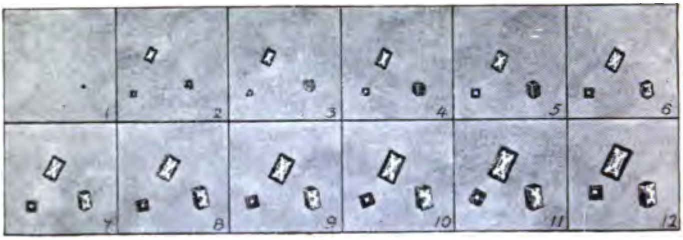

Fig. 51.—Growing Crystals of Potassium Iodide.

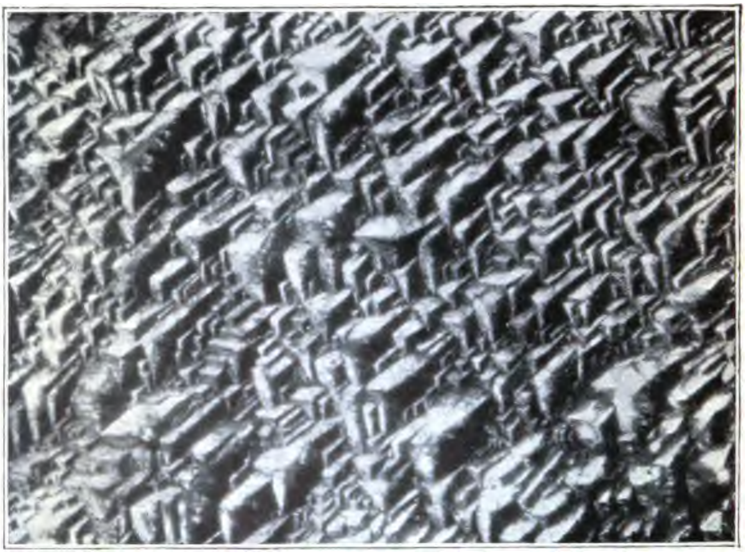

Fig. 53.—Surface of Silicon Steel. (J. E. Stead.)

[*To face p.* 89.

The outward feature of a crystal—regular geometrical form—may be destroyed, and yet the minute fragments which build up the crystal all retain their crystalline characters. The ultimate particles are arranged in a regular and symmetrical manner. Fig. 52 is a sketch of a crystal of the mineral calcite, from which a few crystallites have been broken away so as to show that the larger crystal is built up in the manner just described. Each crystallite, which has been removed, is made up of still smaller crystallites, built up in the same manner. Even if the whole be powdered to dust, each little fragment is a perfect model of the largest.

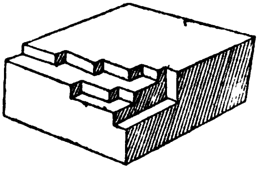

FIG. 52.—Crystal of Calcite.

If the surface of a crystal be suitably treated, the ends of the crystallites may be exposed. The specimen of silicon steel shown in Fig. 53, has been treated with nitric acid. The grouping of the minute elements which make up the specimen is brought out in an interesting manner.

The cause of the splitting of a crystal along its cleavage planes will now be very clear. The planes of weakness in a crystal are naturally along the surfaces joining one crystallite with another. These are the cleavage planes of the crystal.

§ 37. Effects of Progressively Augmented Strain

Ewing and Rosenhain[1] found that if a metal is strained past its "yielding point"—elastic limit—the faces of the crystal grains (Fig. 54) show fine black lines, which increase in number as the strain increases. Lines appear on certain crystals nearly transverse to the pull; but as the strain increases, lines appear upon other grains. Intersecting lines then make their appearance on some of the grains. Such a strained surface is shown in Fig. 55.

What are these lines? Can they be cracks in the surface? Probably not, and for this reason. A piece of iron, strained beyond its elastic limits, will recover[2] its original elasticity if it be allowed to rest for some time, or if it be heated to 100° C. But the dark lines do not disappear. Furthermore, the lines do disappear when the surface is lightly polished in the usual manner.

The lines are not actual cracks in the surface, but rather slips along the cleavage planes of the crystal. They are called slip bands, or slip lines. Let *AB* (Fig. 56) represent a cross-section through a polished surface of metal. Let *C* be the junction between two contiguous grains, *A* and *B*. When the metal is pulled in the direction of the arrows a number of slips are developed along the cleavage planes *a*, *b*, *c*, *d*, . . .,

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[1] J. A. Ewing and W. Rosenhain, *Phil. Trans.*, 193. 353, 1899; 195. 279, 1900; J. A. Ewing and J. C. W. Humfrey, *ibid.*, 200. 241, 1902; W. Rosenhain, *Journ. Iron and Steel Inst.*, 67. i. 335, 1904; F. Osmond and C. Frémont and G. Cartaud, *Revue de Métallurgie*, 1. i. 1904.

[2] J. Muir, *Phil. Trans.*, 193. 1, 1900; *Proc. Roy. Soc.*, 67. 461, 1900.

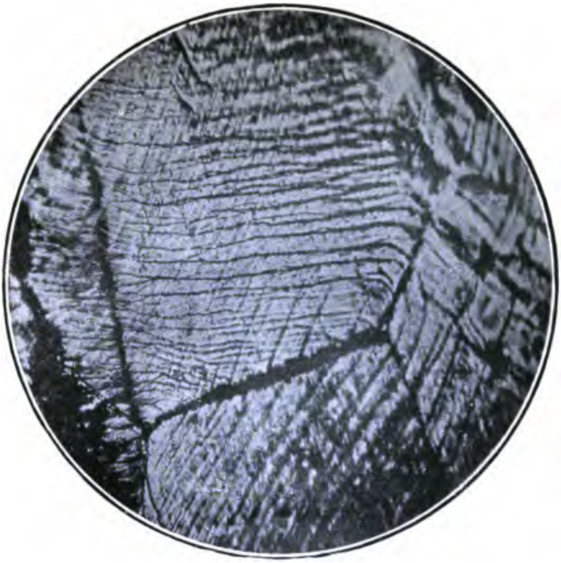

FIG. 54.—Iron. (J. A. Ewing and W. Rosenhain.)

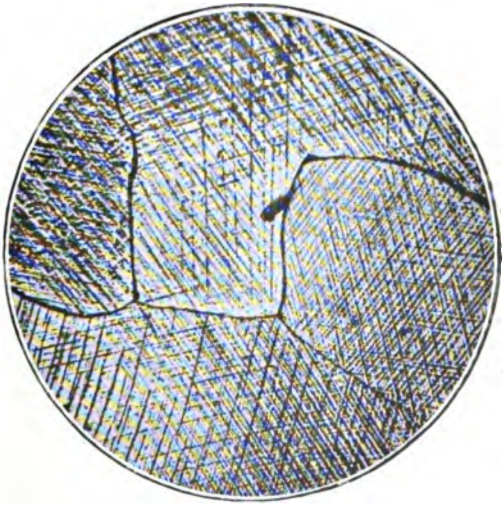

FIG. 55.—Lead. (J. A. Ewing and W. Rosenhain.)

[*To face p.* 90.

and the surface now presents the appearance shown in Fig. 57. With still greater strains slip bands develop into actual cracks, and rupture takes place. Hence it follows that *under a progressively augmented strain rupture takes place, not at the crystal boundaries, but through the crystals themselves.*

Slip-bands have also been developed by compression, say pinching a button of polished silver or copper in a vice, by twisting an iron bar, and by bending a strip of iron or copper backwards and forwards.

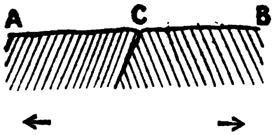

Fig. 56.

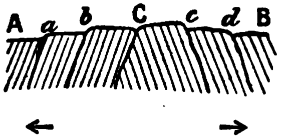

Fig. 57.

Plasticity is nothing but the yielding or slipping past each other of adjoining crystals; ice is only plastic when the strain is directed along the cleavage planes. In a large aggregate of crystals, only those crystals whose cleavage planes are in the right direction will suffer deformation.

You will remember that the elastic limit or yield-point of a body is the maximum distortion which the body can undergo, and yet return to its original form. If the strain is not very much greater than the elastic limit, the restoration of the original form will take place very slowly, as indicated above. The metal exhibits what is called fatigue. Steel bridges, for example, sometimes sag during the week's traffic, but recover during Sunday's rest.

It is possible to apply a much greater stress than the elastic limit of the metal provided the stress be applied very quickly. Thus B. Hopkinson has recently shown that a piece of wire with an elastic limit of 17·8 tons per square inch withstood a stress of 35·5 tons per square inch applied for less than the thousandth part of a second.

§ 38. Effects of Repeated Alterations of Stress

Nearly fifty years ago Wöhler[1] made the important discovery that the elastic limit is very much reduced by, and that metals will even break down undor, the repeated application of a stress very much less than would be required to produce rupture if the stress were applied gradually and continuously. The strength of a piece of metal when tested in the ordinary way is not a sure guide if the material is to be subjected to a series of constantly vibrating stresses—pushes and pulls—such as might occur in the piston of an engine, and the axles of a railway carriage. An iron bar, for instance, which is capable of bearing 20 tons per square inch of steady load can only withstand 9 tons per square inch for six hours if the stress vibrates about 144 times per minute. Bridges which might withstand the passage of a given number of trains per hour could not bear the same number passing in a minute.

The strength of a metal under the influence of alternations of stress depends on the number of alternations per minute; and the number of alternations which a metal can stand depends upon the intensity of the stress. The following table shows the number of

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[1] A. Wöhler, *Engineering*, 11. 199, 221, 243, 299, 326, 349, 1871; A. W. Kemp, *Engineering Review*, 11. 168, 1904.

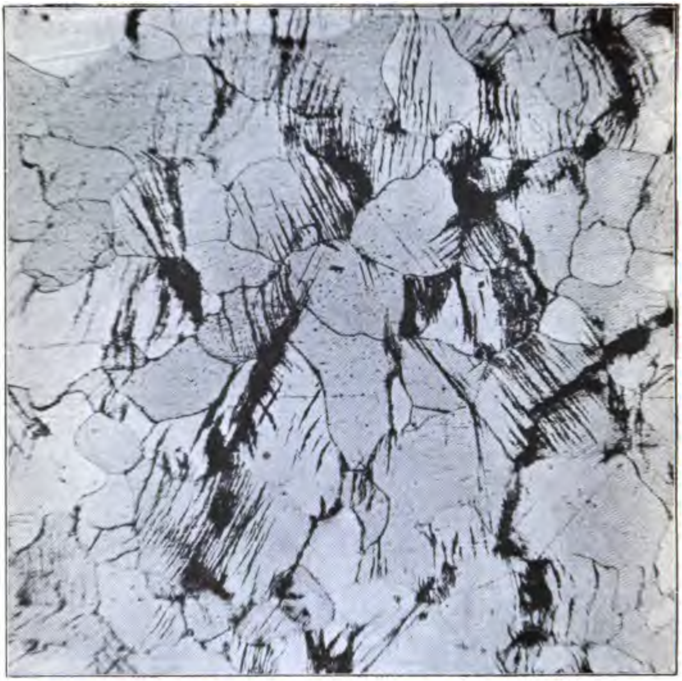

Fig. 59.—Slip-bands multiply.
(J. A. Ewing and J. C. W. Humfrey.)

[*To face p.* 93.

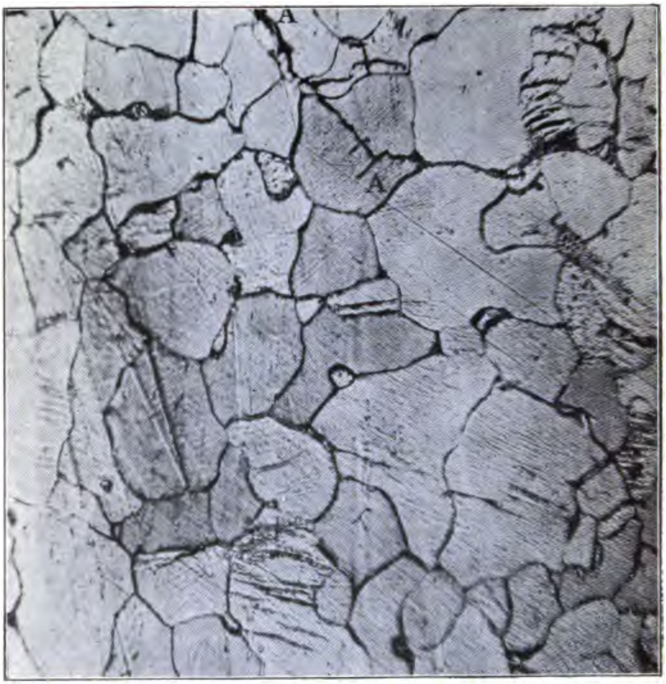

Fig. 60.—Polished Surface with Small Cracks.
(J. A. Ewing and J. C. W. Humfrey.)

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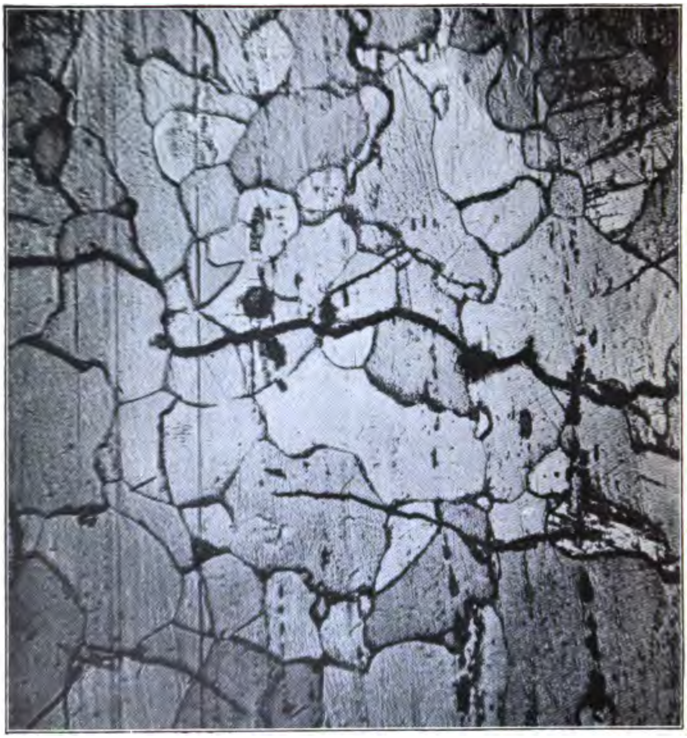

Fig. 61.—Polished Surface with Large Crack.
(J. A. Ewing and J. C. W. Humfrey.)

To face p. 93.

alternations of stress which is required to rupture when the stress is applied 144 times per minute:—

Tons per square inch.	Number of revolutions.
15·3	56,000
14·4	99,000
13·4	183,000
12·4	480,000
11·5	910,000
10·5	3,632,000
9·6	4,918,000
8·6	19,187,000

Ewing and Humfrey have subjected Swedish iron, with a breaking stress of 23·6 tons per square inch, to a series of pushes and pulls, 9 tons in magnitude, repeated 400 times per minute. On examination it was found that fine slip-bands appeared in a few crystals after a few—say 5000—reversals of stress, as shown in Fig. 58. With a greater number of reversals—say 40,000—the slip-bands increase in number, and those which first appeared broaden and develop into small cracks, as shown in Fig. 59. If the specimen be repolished, so as to clear off the slip-bands, the cracks alone become visible, as at *A* (Fig. 60). The crack, or flaw, gradually creeps right across the specimen when the number of alternations is still further increased, as shown in Fig. 61. Finally, the specimen breaks. Let me quote Ewing and Humfrey's own words:—

"Whatever the selective action of the stress is due to, the experiments demonstrate that in repeated reversals of stress certain crystals are attacked, and yield by slipping, as in other cases of non-elastic strain. Then, as the reversals proceed, the surfaces upon which the slipping has occurred continue to be surfaces of weakness. The parts of the crystal lying on the two sides of each such surface continue to slide back and forth over one another. The effect of this repeated sliding or grinding is seen at the polished surface of the specimen by the production of a burr or rough and jagged irregular edge, broadening the slip-band, and suggesting the accumulation of *débris*. Within the crystal this repeated grinding tends to destroy the cohesion of the metal across the surface of the slip, and in certain cases this develops into a crack. Once the crack is formed, it quickly grows in a well-known manner, by tearing at the edges, in consequence of the concentration of stress which results from lack of continuity. The experiments throw light on the known fact that fracture, by repeated reversals or alternations of stress, resembles fracture resulting from 'creeping flaw' in its abruptness, and in the absence of local drawing-out, or other deformation of shape."[1]

The rupture of steel is not caused by the gradual growth of the crystalline structure of the metal under the influence of shocks and vibrations. The break-down is due to fatigue. When fatigued, the metal breaks more readily. Again, when subjected to sudden shock, the metal has no time to "flow." The slipping of the crystal planes, or the plasticity of the metal, has no time to come into play. The metal, in consequence, appears to be abnormally brittle.

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[1] P. Kreuzpointer, *Journ. Franklin Inst.*, 153. 233, 1902; J. A. Ewing, *Nature*, 70. 187, 1904; P. Breuil, Suppl., *Journ. Iron and Steel Inst.*, 1904.

DEMONSTRATION: HOW TO PREPARE A SPECIMEN FOR THE MICROSCOPE

§ 39. The Cutting of a Sample

The piece of steel to be examined must be dressed up to a suitable size for microscopic examination. It is impracticable to examine the whole area of a large piece. The usual thing is to work with a circular or square surface having an area of about $\frac{1}{4}$ or $\frac{3}{8}$ sq. in. The specimen should be about half an inch thick.

The size of the grain in a bar of steel varies from the centre to the outside. Samples must therefore be cut from definite positions if one specimen is to be compared with another. Notice whether the sample is cut parallel with, or across the direction of rolling. Do not cut a sample near a distorted part with an abnormal grain.

An American hack saw may be used for cutting soft alloys and unhardened steel. White cast iron and hard brittle alloys are best split with a blow from a hammer. It does not matter much how irregular the piece is, since only one surface is required for examination.

§ 40. Filing and Rough Polishing

The next step is to fasten the specimen in a suitable vice. File one side with a "rough" file, then with a "smooth" file, and finally with a "dead smooth" file. The marks from each file should be across those made by the preceding file, and also obliterate them.

The filing is followed by a series of polishings with emery papers of increasing fineness. Start with "No. 1," and finish off with "No. 0," "No. 00," and "No. 000." The emery paper may be fixed upon wooden discs or blocks with hot glue. Each set of scratches should obliterate and run across those made by the preceding set. Be careful to keep the polished surface as flat as possible.

This operation is rather important on account of its influence upon subsequent work. The metal should now have a distinct polish, and the scratches be only faintly visible.

§ 41. Fine Polishing

The discs or beds used for fine polishing must be sufficiently yielding to come in contact with the whole surface, and not press hard enough to grind out the softer constituents and leave the harder constituents too much in relief. A flat disc of wood, metal, glass, or ebonite covered with a layer of cloth, velvet, or chamois leather gives good results.

A little diamantine powder may be rubbed on the covering of the disc, and the disc kept moist with water. The specimen is pressed upon the bed and constantly turned so as to avoid the formation of furrows.[1] Examine the specimen from time to time in a good light, and when all the scratches are removed, polish the specimen on a chamois leather bed upon which fine gold rouge has been rubbed.

The polishing materials, beds, etc., should be critically examined to make sure that they will not scratch a polished surface. Preserve all polishing materials in a place protected from dust.

Instead of diamantine and rouge, some use a paste made of "one day" alumina powder and Castile soap.

PREPARATION OF POLISHING POWDER.—The powder can be purchased from the dealers, or made in the following manner:—

Calcined ammonia alum is treated with water acidified with nitric acid (one part of acid to 1000 c.c. of water) for a few hours with occasional stirring. Use about 10 grams of powder for every litre of water. Decant off the clear. Treat with distilled water in a similar manner, and repeat until all the acid is removed and the settling takes place slowly. Now add 2 c.c. of aqueous ammonia per litre of water, and let settle. Decant off with a syphon at stated intervals, namely, 15 min.; 1 hr.; 4 hrs.; 24 hrs.; 8 days.

The deposit remaining after the first decantation contains all the coarse grains not suitable for polishing. The deposit after the second decantation is not very homogeneous, but it is useful for coarse polishing. The deposit remaining after the liquid has stood four hours can be used for hard metal, like iron. The one and eight day deposits make the best polishing powders.

Shave dry Castile soap with a clean knife into powder. Add one part of dry soap to ten parts of wet powder. Melt on a water bath. Let cool with constant stirring until the mass thickens. Pour into leaden tubes like those used for keeping oil paints. The tubes may be closed up when cool.

§ 42. Polishing in Relief

If the prepared surface be quite level and of a uniform tint, it would not be possible to distinguish one constituent from another. All varieties of iron and steel would appear to be identical. In order to distinguish one constituent from another it is necessary to treat the polished surface with some medium which will dissolve certain constituents and leave others untouched. Such a medium is called an etching fluid, and the surface, after treatment with etching fluid, is said to be etched.

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[1] Special machines are on the market which do this work automatically.

Usually the softer constituents are more worn than the harder constituents. Hence the surface is a little uneven. This is called polishing in relief. It is sometimes possible to see the structure of such a surface when it is examined in a convenient position without any further treatment. For relief polishing use a bed of indiarubber, free from grit, glued upon a wooden block.

There is another point to be noticed. The operations of polishing produce a thin film on the surface which is essentially different from the body lying underneath. For instance, the surface of polished speculum metal presents the appearance of Fig. 62, but when the surface film is removed by washing it with a solution of potassium cyanide, the true structure of the metal appears as shown in Fig. 63.[1]

§ 43. Etching

Etching on a surface which has been touched with the fingers or any other greasy surface is misleading, because the surface is more or less protected from the etching fluid. To clean an oily or greasy surface,

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[1] G. T. Beilby, *The Electrochemist and Metallurgist*, 3. 827, 1904.

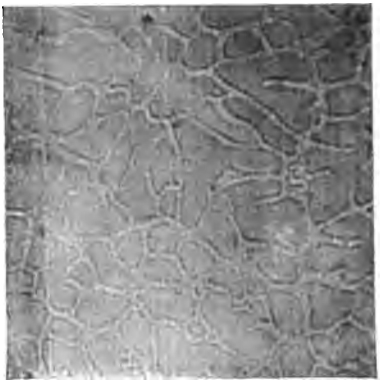

Fig. 62.—Polished Speculum Metal. (G. T. Beilby.)

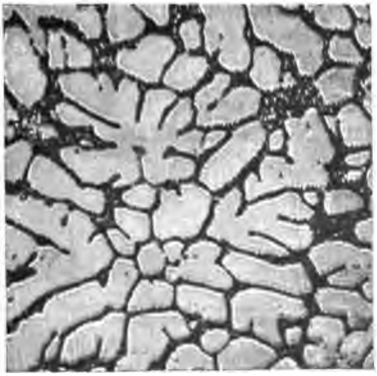

Fig. 63.—Etched Surface of Speculum Metal. (G. T. Beilby.)

[*To face p.* 98.

wash it in alcohol or ether, and dry. If the surface is clean no "rim" will be discernible when a drop of ether is allowed to evaporate on the surface.

Different workers prefer different etching fluids. Tincture of iodine, and dilute nitric acid are most frequently used.

I. Iodine.—Osmond employs tincture of iodine of two different strengths. The first contains

Iodine	1·25 grms.
Potassium iodide	1·25 grms.
Water	1·25 grms.
Alcohol to make up to	100 c.c.

The second solution is made by diluting 25 c.c. of this up to 100 c.c. with alcohol. The stronger solution is used for mild steels, the more dilute solution for hard steels.

To apply the solution proceed as follows. Rub the solution over the polished specimen with the tip of the finger, or with a camel's-hair brush, and stop the etching when the brilliancy of the polished surface disappears, and the surface appears dull and grey. By rubbing the polished specimen in this manner, the etching is more uniform, and the constituents not acted upon by the etching fluid remain bright. Wash the specimen in alcohol, and finally dry in a blast of hot air, from, say, a Fletcher's hot-blast blowpipe.

If this treatment has not been sufficient to develop the structure, repeat the operation. Several mild etchings are better than one severe process. The etching which results from a prolonged exposure to the etching fluid often depends not so much upon the structure as upon mechanical imperfections of the surface, and other external causes. The lines of demarcation between the different constituents are frequently indistinct and blurred. If on examination the etching is too deep, it will be necessary to repolish the surface. Deep etching is frequently misleading.

II. Nitric Acid.—Sorby used dilute nitric as an etching fluid. This is generally recognized as one of the best agents for steels containing but little phosphorus or arsenic. The strength may be—

Nitric acid (sp. gr. 1·42)	10 grms.
Water up to	100 c.c.

Hold the specimen by means of a pair of crucible tongs, and immerse in the acid for about ten seconds. Wash in running water, then immerse in lime-water, then in water again, then in alcohol, and finally dry with hot air.

A. Sauveur[1] adds: "The unreliableness and shortcomings of the usual treatment with dilute nitric acid are overcome by dipping the specimen in concentrated nitric acid (sp. gr. 1·42), which, on account of passivity, has little or no action on the polished surface. The specimen is then placed under an abundant stream of running water, and the acid is quickly and completely washed off. As soon as the layer of concentrated acid which covers the surface is diluted by the running water, it attacks the steel, at first vigorously, but for such a short time (since the water soon removes all traces of acid) that there is no danger of etching too deeply. This develops the structure clearly and sharply, the etching being of a uniform intensity all over the surface, and free from the objectionable coloured film, and from the unlike appearance of different parts of the field caused by local actions of varying intensity, which are so troublesome and misleading in etchings with dilute acid. It is sometimes necessary to repeat the treatment in order to develop structure to a proper depth, but more than two immersions are seldom required. The specimen is washed in water, alcohol, and quickly dried with a soft cloth, or under a hot jet of air."

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[1] A. Sauveur, *Metallographist*, 3. 231, 1900.

An alternative[1] way of conducting the etch with nitric acid is to employ the solution—

Nitric acid (sp. gr. 1·42)	1 grm.
Absolute alcohol	99 grms.

Arnold[2] treats a specimen with nitric acid (sp. gr. 1·20) immediately after leaving the No. 00 emery pad until bubbles of gas make their appearance (about one minute). The scratches are nearly all removed, and the structure is well enough defined for most commercial purposes. The preparation of a piece of steel for microscopic examination by this method only takes about five minutes.

III. Picric Acid.—A favourite etching fluid is prepared from—

Picric acid	5 grms.
Absolute alcohol	95 grms.

as recommended by Igevsky. It brings out the cell walls very distinctly. It does not colour ferrite.

IV. Hydrochloric Acid.—A solution is prepared by passing dry hydrochloric acid hydrogen chloride into absolute alcohol until the solution contains about 10 per cent. of acid. Then add one to 5 per cent. of anhydrous cupric chloride. Use solutions containing the least amount of cupric chloride for hard steels. Let one or two drops of this solution fall on each square centimetre of surface, and let the attack continue until the surface is covered with a light grey film. Wash and dry as before.

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[1] F. W. Spiller, *Metallographist*, 6. 264, 1903, replaces the alcohol by glycerine.

[2] J. O. Arnold, *Nature*, 63. 618, 1901.

Other acids may be used—sulphuric, oxalic, chromic (Abel)—but all are inferior to nitric and picric acids.

V. Electrochemical Attack.—Very good results have been obtained by immersing the metal in a 10 per cent. solution of ammonium chloride, potassium sulphate, or warm sodium thiosulphate, while it is connected with the positive pole of a bichromate cell, the negative pole consisting of a piece of platinum foil, lead foil, or thin sheet iron. The current used varies from 0·001 to 0·01 ampere per sq. cm. of surface. The current should last a few minutes.

§ 44. Osmond's Polish Attack

Osmond recommends a lubricating solution of—

Cryst. ammonium nitrate	2 grms.
Water	100 grms.

in place of water in the last stage of the polishing with a parchment pad and rouge. The ammonium nitrate does not alone act upon the metal, but chemical action is induced by rubbing and friction.

An aqueous infusion of liquorice root was formerly used, but this has been abandoned in favour of ammonium nitrate.[1]

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[1] F. Osmond and G. Cartaud, *Metallographist*, 3. 1, 1900.

Ferrite and cementite are not coloured by iodine; the remaining four constituents—sorbite, troostite, martensite, and austenite—are coloured. The intensity of coloration depends upon the amount of carbon present. Sorbite is coloured first, troostite next, and martensite and austenite last.

Ferrite, cementite, martensite, and austenite are not coloured by the polish attack. Martensite takes a yellowish tint. Martensite differs from pearlite in the fact that the martensite needles intersect; pearlite laminæ do not intersect. Troostite is always accompanied by martensite, sorbite by pearlite. Ferrite and cementite differ in their unequal degree of hardness under the polish attack.

PROPERTIES OF CONSTITUENTS.

Constituent.	Polish attack.	Iodine.	Nitric acid.	Remarks.
Ferrite	Granular	Colourless	Polygonal structure	Softer than other constituents; coloured by nitric acid, while cementite is not.
Cementite	Nil	White	No action in 40 sec. with 20% acid	Harder than other constituents; not coloured by nitric acid, while ferrite is.
Martensite	Intersecting needles appear	Coloured slowly	Yellowish	Unlike pearlite, has straight intersecting fibres.
Pearlite	Curved lamellæ	Dark	Dark	Unlike martensite, fibres are curved and never intersecting.
Troostite	Yellow brown to blue bands	Coloured faster than martensite	Dark yellow	Accompanies martensite, and is coloured more slowly than sorbite.
Sorbite	Coloured	Coloured faster than troostite	Dark	Accompanies pearlite, and is coloured more quickly than troostite.
Austentite	Nil	Coloured	Lighter yellow than martensite	Martensite goes yellow, brown, and black when treated by electrochemical attack.

§ 45. Heat Tinting

By heating polished sections of any metal, the various constituents are differently coloured. The colouring depends upon the formation of films of oxides which have different colours. The colours are formed at different rates on the different constituents of the metal. This method of studying the constitution of alloys has been used with success by Martens, Behrens, Osmond, and Stead.

The polished specimen is well rubbed with a piece of clean linen or chamois leather, warmed to about 120°, and again well rubbed. The heating is done on an iron plate about six inches square, heated over a Bunsen burner. Experience will show how much heating is required to colour the specimen. The heating is best done gradually. Cool the tinted specimen in a dish of mercury to prevent oxidation during cooling.

Stead used the process in his work on the phosphatic steels.[1] By heating a phosphatic steel until the pearlite is blue, the cementite will be red and the phosphide yellow. Experience shows that it is best to etch the specimen with iodine before heat tinting, so as to darken the pearlite, and after wiping with a chamois leather or linen rag, heat until the pearlite is dark.

§ 46. Mounting

The specimen may be mounted on a ground-glass plate imbedded in a piece of beeswax or a piece of plasticene; or, better still, use a "mechanical holder."

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[1] J. E. Stead, *Journ. Iron and Steel Inst.*, 58. ii. 60, 1900; *Metallographist*, 4. 89, 199, 332, 1901.

Sorby used to make his specimens about 1 sq. cm. and 2 mm. thick. Fix a flat surface on a small glass plate by warming a small fragment of *hard* Canada balsam on the glass plate while the latter rests on a warm iron plate. Then remove the glass plate from the iron plate, and press the specimen upon the balsam until it has set hard. The exposed surface can then be polished with emery paper, etc.

§ 47. Preservation of Polished Specimens

Some preserve polished surfaces from rust by immersion in oil; others cover the surface with a solution of paraffin wax in benzene. To remove the wax, wipe the surface with a clean rag moistened in benzene, and finally rub it with a dry linen rag.

Le Chatelier recommends the use of a varnish made by dissolving gun-cotton in amyl acetate. The coating of varnish is transparent, and it will allow the specimen to be examined with the high powers. The protective film lasts many months.

The specimens may be stored in pill-boxes or other convenient receptacle, suitably labelled; the label should contain a full history of the specimen, mode of treatment, etching fluid, and date.

§ 48. The Microscope and its Accessories

The microscope selected is decided very much by the available cash. The best thing is to consult the dealers' catalogues. The price of the outfit will range from £16 upwards. The student is also advised to buy a small handbook on microscopic manipulation.

The specimen to be examined by the microscope is opaque, and it is necessary to illuminate the surface before it can be examined in a satisfactory manner. Two methods of illumination are used :—

I. Oblique Illumination.—Chiefly used for the low powers. Here the light *L* (Fig. 64) is reflected on to the surface *S* from the reflecting shield *R*, which partly surrounds the objective *O*. The path of a ray of light travels in the direction of the arrows and the dotted line, up through the eyepiece.

II. Vertical Illumination.—Chiefly used for the high powers. The light *L* (Fig. 65) is admitted through the aperture *A* at the side of the object glass, and is reflected downwards on to the specimen *S*, from the reflecting surface at *R*. The light then passes through the prism to the eyepiece. An iris diaphragm is fixed at the aperture *A*, so as to regulate the amount of light admitted to the specimen. The dealers' catalogues will furnish full particulars.

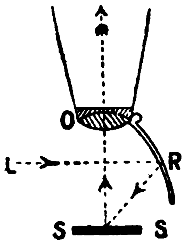

FIG. 64.

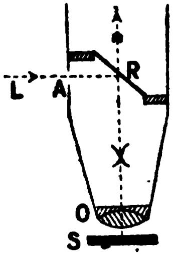

FIG. 65.

It is necessary to have command of a brilliant light, say an arc lamp, an incandescent lamp, a

Welsbach, or an acetylene light. A Nernst lamp is frequently recommended very strongly. A bull's-eye condenser should be placed between the reflector and the source of light, so as to concentrate the rays.

§ 49. Photography

Here, again, the dealers' catalogue must be consulted. The price of a camera ranges from 25*s.* upwards. You must also consult some handbook on the subject of microphotography—say, W. Bagshaw's *Elementary Microphotography* (London, 1902, 1*s.*).

§ 50. Miscellaneous

Risdale considers the following is a fair approximate allowance for the successive operations required in preparing a microphotograph of the structure of a given metal—

Sawing off the section	From	1	to	5	min.
Grinding and polishing	„	15	„	30	„
Polish examination	„	2	„	3	„
Etching and washing	„	3	„	5	„
Examination and photography	„	7	„	10	„
Developing, fixing, rinsing, and drying negative	„	15	„	15	„
Printing	„	2	„	2	„
Developing, fixing, and rinsing print	„	15	„	20	„
Total		1	to	1½	hrs.

The following are a few useful papers and books on this subject:—

C. H. Risdale, *Journ. Iron and Steel Inst.*, **56**. ii. 102, 1899.
J. E. Stead, *Metallographist*, **3**. 220, 1900.
H. le Chatelier, *ibid.*, **4**. 1, 1901.

M. A. Richards, *Metallographist*, 6. 71, 1903.
J. Beck, *ibid.*, 6. 320, 1903.
H. C. Carpenter, *Technics*, 1. 489, 1904.
A. H. Hiorns, *ibid.*, 1. 19, 1904; *Metallography*, London, 1902.
F. Osmond, *Metallographist*, 1. 5, 1898; *Microscopic Analysis of Metals*, London, 1904 (J. E. Stead's translation).

The following list has been prepared by W. Watson & Sons, 313, High Holborn, London, W.C. It gives a rough outline of the necessary items on which an outfit can be formulated—

Preparing and Polishing Machines: Many of the parts of machines for preparing and polishing are to be found in every workshop, but all the contrivances are made to work with foot or hand, as well as by power—

	£	*s.*	*d.*
Hack saw (found in all workshops).			
Set of files and vice (found in every workshop).			
Power-driven polishing machine with automatic head	5	10	0
A machine similar to this, for foot power, costs . .	8	10	0
Where a quantity of work is to be undertaken, a machine with three automatic heads, and five tables, power driven, can be purchased for . .	14	15	0
In addition, a set of suitable polishing materials is essential. These are usually put up in small boxes, consisting of two or three grades of emery-paper, together with wash-leather vellum, etc., for polishing. A set of these usually costs. . .	0	10	0

The Microscope Outfit: The microscope outfit should consist of—

	£	*s.*	*d.*
Microscope stand, with vertical illuminator and a covering stage, which may vary in price from . .	13	10	0
		to	
	30	0	0
In addition, a good form of metal-holder, which permits of small sections of metal being gripped and set at any desired plane from the objective, will be found a necessity	1	4	0
The objectives that are regularly used are the 1″, $\frac{1}{6}$″, and $\frac{1}{12}$″. These vary very considerably in cost.			

The so-called Student's lenses are usually considered sufficient for the purpose, and cost—

	£	s.	d.
1″ . . .	1	2	0
$\frac{1}{6}$″ . . .	1	10	0
$\frac{1}{12}$″ . . .	5	0	0

Where, however, expense is not of importance, and the best possible is desired, Zeiss Apochromatic objectives should be procured, and the set that would be recommended then would be—

1″ . . .	6	0	0
$\frac{1}{4}$″ . . .	9	0	0
$\frac{1}{6}$″ (dry) .	15	0	0
$\frac{1}{12}$″ (oil immersion) .	15	0	0

All objectives, excepting only the 1″, should be ordered to be corrected for use on uncovered objects for metallurgical work.

With the Student's lenses, ordinary Huyghenian eyepieces are suitable, and cost, each . . . 0 10 6

But with the Zeiss Apochromatic objectives it is absolutely essential that compensating eyepieces be employed, and the cost of these would be—

× 4 . . .	1	5	0
× 8 . . .	1	15	0
× 12 . . .	1	10	0

It will also be found necessary to have some form of object changer, and for metallurgical work it has generally been found that those by Zeiss are the most convenient. A holder is attached to the nosepiece of the microscope, and a suitable fitting is provided for each objective. The slider and changers cost, each 0 10 0

A new form of objective changer called the "Facility," has been introduced by W. Watson & Sons. It is equally convenient and costs 1 15 0

To illuminate specimens, the vertical illuminator, which is provided with the microscope, is necessary for medium and high power work. For low powers, the illumination should be by means of a side silver reflector, the light being condensed upon it by means of a bull's-eye, which latter will also be applicable when using the vertical illuminator. The cost of the reflector, with a Sorby

	£	s.	d.
prism, which allows of oblique illumination, would be.	1	15	0
A plain form of bull's-eye, with Iris diaphragm, costs	1	10	0
The rapidity with which work can be done can be greatly increased by using a bull's-eye with mechanical adjustments, this costs . . .	4	0	0

The Photographic Outfit: Many workers prefer to photograph metallurgical specimens in the vertical position only, while others advocate the horizontal position as the best.

	£	s.	d.
There are cameras made which can be used in both the vertical and horizontal positions, and the cost of such a one is	7	15	0
A first-class camera for use in the horizontal position only, would cost	11	10	0
A projection eyepiece is also necessary for photographing, and costs	2	0	0
A focussing glass for examining the specimen on the ground-glass screen, costs about	0	8	0

APPENDIX

Glossary

THE following glossary of terms is based upon the *Report on the Nomenclature of Metallography*, drawn up in September, 1901,[1] by the Iron and Steel Institute. The French (F.) and German (G.) equivalents are usually given.

Ac_1, Ac_2, Ac_3. (The "c" comes from the French *chauffant* = heating.) Critical points in heating curve of iron and steel.

Acicular (*acus* = needle). Needle-like. Applied to needle-like crystals found in cavities in ferromanganese, basic slags, etc.; and not to needle-like structures observed in sections of metals and alloys. (G. *nadlig*; F. *aciculaire.*)

Air pits. Term applied by Ewing and Rosenhain to microscopic air bubbles which appear on the surface of certain metals cast on glass. (G. *Luftgrübchen.*)

Allotriomorphic (*ἀλλότριος* = strange; *μορφη* = form). A term applied to crystals which have taken their shape from their surroundings. (G. *allotriomorph*; F. *allotriomorphe.*)

Allotropy (*ἄλλος* = other; *τρέπειν* = to turn). A term applied to an element which exists in two or more forms having different physical properties at the same temperature. The term is not applied to differences in the state of aggregation of an element. (G. *Allotropie*; F. *allotropie.*)

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[1] *Journ. Iron and Steel Inst.*, 61. i. 99, 1902; *Metallographist*, 5. 145, 1902.

Alloy (Old Eng.). A metallic alloy is an intimate mixture or union of metallic substances which do not separate into two distinct liquid layers on melting. (G. *Legierung*; F. *alliage métallique.*)

Alpha iron, or α-iron. The normal and stable condition of iron below 750° C. Crystallizes in the cubic system. Is soft and magnetic. (G. *Alpha-eisen*; F. *fer alpha.*)

Amorphous (α = without; μορφη = form). Non-crystallized. (G. *amorph*; F. *amorphe.*)

Aphanitic (ἀφανής = invisible). A texture on which the component grains are so minute as only to become visible under the microscope. (G. *aphanitisch*; F. *aphanitique.*)

Ar_1, Ar_2, Ar_3. (The "r" comes from the French *refroidissant* = cooling.) Critical points in the cooling curve of iron and steel.

Arborescent (*arborescere* = to become a tree). Tree-like. (G. *tannenbaumförmig*; F. *arborescent.*)

Austenite (in honour of W. C. Roberts-Austen). A constituent of steel. Produced when iron containing more than 1·5 per cent. of carbon is suddenly quenched in cold water from 1100° C. It is softer and less magnetic than the martensite with which it is always associated. A needle drawn across a polished surface scratches austenite more deeply than martensite. Under Osmond's polish attack with ammonium nitrate, austenite remains white; martensite turns brown, with fibres having zigzag appearance. Jüptner von Jonstorff considers austenite to be a solution of atomic carbon or ionized iron carbide in iron. (G. *Austenit*; F. *austenite.*)

Bacillar (*bacillum* = little rod). Rod-shaped. (G. *stäbchenförmig*; F. *bacillaire.*)

Beta iron, or β-iron. An allotropic form of iron stable between 860° and 700° C. Isomorphous with alpha iron. Is hard and non-magnetic. (G. *Beta-eisen*; F. *fer bêta.*)

Blowholes. Small cavities—spherical or ellipsoidal—found in ingots of cast metals. They are due to bubbles of gas which have not been able to escape before the metal became completely solid. (G. *Blasenhohlräume, Blasen ;* F. *soufflures.*)

Brittleness (Old Eng.). Property of being more or less easily broken. Caused by want of cohesion between cleavage planes of crystal grains or their joints. (G. *Brüchigkeit ;* F. *fragilité.*)

Burned (Old Eng.). Applied to a metal which is brittle in consequence of a chemical alteration of its mass due to excessive heating. The sp. gr. of burnt steel is less than the original metal, because the evolution of gas in the solid metal has separated some of the crystal grains one from the other. The carbon is generally low near the external surface. Oxide of iron may be often detected on the surface of the grains. Steel may be burnt by heating in an inert atmosphere. Oxidation is then impossible. Burnt steel is generally —not always—coarsely granular and easily fractured. (G. *verbrannt ;* F. *brulé.*)

Cancellated (*cancellare* = to make a lattice). Latticed; that is, crossed by two series of parallel lines. (G. *gitterförmig ;* F. *formé en treillis.*)

Capillary (*capillus* = a hair). A hairlike structure.

Carbon (*carbo* = coal). Several varieties of this element occur in iron and steel.

1. *Carbide carbon, or combined carbon.* The condition in which carbon occurs in cementite. Jüptner von Jonstorff distinguishes three varieties of combine carbon, di-, tri-, and tetra-carbon. (G. *Carbidekohle ;* F. *carbon du carbure.*)

2. *Annealing or temper carbon.* Finely divided carbon having the properties of graphite which separates from white cast iron and certain steels on prolonged annealing, and, according to Ledebur, from high carbon steel when it is raised to a red heat by rapid hammering. "Temper" in German has a different meaning to the English word "temper." "Annealing" is the best term to use. (G. *Temperkohle ;* F. *carbon de recuit.*)

3. *Graphitic carbon.* The carbon which separates

from highly carburized molten iron during solidification. (G. *Graphit*; F. *graphite*.)

4. *Missing carbon*. That carbon in hardened and tempered steels which does not give a coloration when steel is dissolved in nitric acid of sp. gr. 1·20.

5. *Hardening carbon*. The condition of carbon which confers hardness to steel when quenched from above Ar_1. It is said to be combined carbon. (G. *Härtungskohlenstoff*; F. *carbon de trempe*.)

Cellular (*cellula* = a little cell.) Containing irregular spheroidal or ellipsoidal cavities. Applied to net-like or a meshed structure. (G. *zellig*; F. *cellulaire*.)

Cementite, A name given by H. M. Howe to the iron carbide which, according to the works of Abel, Müller, and Osmond, has the formula Fe_3C. The term is used in a general way for all the carbides which exist in cast iron and steel, whether these carbides contain manganese chromium, etc. Cementite exists in granules, thin plates, or in comparatively hard masses. Its hardness on Mohs' scale is 6. Is not coloured by polishing or etching with dilute nitric acid, iodine solution, hydrogen chloride, or alcohol, etc. The cementite which is a constituent of pearlite, has been called "segregated" cementite (Sauveur); the cementite which occurs independently is then called "free" cementite. It is, perhaps, better to call the former "pearlite-cementite," the latter "excess cementite." (G. *Cementit*; F. *cémentite*.)

Cleavage (Old Eng.). The property possessed by crystals and crystal grains of splitting more readily in certain directions than in others. These directions are called cleavage planes. The cleavage planes are not necessarily related to the external faces of the crystals. (G. *Spaltbarkeit*; F. *clivage*.)

Cohesion (*cohærere* = to stick). The force of attraction by which particles are held together. (G. *Kohäsion*; F. *cohésion*.)

Cold-short. Cold-short steel is steel which is weak and brittle when cold. (G. *kaltbrüchig*; F. *cassant à froid*.)

Conchoidal (κόγχη = shell, εἶδος = form). Shaped like a shell. Applied to the concave and convex fractures of some alloys of zinc and copper, tin and copper, glassy slags, etc. (G. *muschlig ;* F. *conchoïdal.*)

Congealed solution. A homogeneous solution after solidification, irrespective of whether the constituents of the solution in the latter state form a mixture or a solid solution in the true sense of the word. Do not confuse with solid solution, *q.v.* (G. *errstarrte Lösung ;* F. *solution congélée.*)

Constituent (*constituere* = to constitute). The structural parts of which alloys and metallic substances are built. Alloys containing only two or more elements or components may have three or more constituents. (G. *Bestandtheile*, *Gefügebestandtheile*, *Gefügebildner ;* F. *constituant.*)

Cooling curve. A graphic representation of the thermal changes which occur when liquid or solid substances cool from a higher to a lower temperature, and in which time and temperature are co-ordinates. Cooling curves may be represented in several ways :—

1. Take temperature, θ, and time, t, reckoned from the commencement of cooling, as co-ordinates.

2. Take temperature, θ, and the time required for cooling down from that temperature through a definite number of degrees, as co-ordinates.

3. Take temperature, θ, and the difference between the time required for the cooling of the metal under investigation, and the time necessary for cooling some other metal (say, platinum), as co-ordinates. These are sometimes called *differential cooling curves.* (G. *Abkühlungskurve*, *Kühlungkurve ;* F. *courbe de refroidissement.*)

Critical points. The points at which a physical or chemical change takes place. For instance, in the cooling of pure iron or steel from 900° C. an evolution of heat occurs at the points designated Ar_3 and Ar_2. This indicates that a physical change occurs at these temperatures. If the change occurs not at one fixed point, but extends over several degrees, the interval is called a *zone.* (G. *kritische Punkte*, *Haltepunkte ;* F. *points critiques.*)

Cryptocrystalline (*κρυπτός* = hidden). When the crystalline form of a substance is so fine that only traces of the crystalline structure can be detected, even under the microscope.

Crystal (*κρύσταλλος* = crystal, ice). This term, as distinguished from mere geometrical solids, is the invariability of the angles between corresponding faces in different individuals of the same substance. The term is sometimes used for particles of crystals, allotriomorphic crystals, pseudomorphic crystals, and crystallites. (G. *Krystall*; F. *cristal.*)

Crystal grain. An allotriomorphic crystal, or a fragment of crystal devoid of its crystal faces and angles. (G. *Krystallkorn*; F. *grain cristallin.*)

Crystalline. In crystallography the term refers to the physical properties of crystallized matter, and is applied to any body, or portion of a body, which possesses these properties, without regard to the external form. In petrology the same word refers to mineral aggregates which consist of crystallized substances, whether in the form of perfect crystals, or merely as grains possessing the physical properties of crystals. (G. *krystallin*; F. *crystallin.*)

Crystallite. A word used with several different meanings. For example, it is used for all indefinitely crystalline or incipient forms of individualization of minerals; imperfect crystals in which the plane faces and angles are not developed; and for the crystal elements which build up the crystal. (G. *Krystallit*; F. *cristallite.*)

Crystallized. Refers to any substance, whatever the external form, which has been produced by a process of crystallization, and which possesses the physical properties of crystallized matter. (G. *krystallisirt*; F. *cristallisé.*)

Cuboidal. Cube-shaped. Applied to crystals which *appear* to have the form of a cube in certain microsections of alloys. (G. *würfelförmig*; F. *à peu près de la forme d'un cube.*)

Cuneiform or Cuneate (*cuneus* = a wedge). Wedge-shaped (G. *keilförmig*; F. *cunéiforme.*)

Cuspidate (*cuspis* = a point). Spear-shaped; tapering abruptly. (G. *speerförmig*; F. *terminé en pointe.*)

Dendritic (*δένδρος* = a tree). Tree-like. See "Arborescent." (G. *dendritisch, verästelt*; F. *dendritique.*)

Druse (*druse* = bonny—Ger.). A cavity having its interior surface studded with crystals. (G. *Druse*; F. *géode.*)

Ductility (*ducere* = to lead). The property of metals to elongate and bend. "Those metals and alloys in which sliding can take place along the cleavage planes without separation occurring." (G. *dehnbarkeit*; F. *ductilité.*)

Elastic limit. The maximum stress a substance will bear without suffering permanent deformation, distortion, or fracture. Usually expressed in tons per square inch, or in kilograms per square millimetre. (G. *Elasticitätsgrenze*; F. *limit d'elasticité.*)

Elasticity (*ἐλαύνειν* = to drive). The property of a substance in virtue of which it tends to recover its size and shape after distortion. (G. *Elasticität*; F. *elasticité.*)

Elasticity, Modulus of. If a rod or wire of length l be stretched until it becomes $l + 1$, then $\frac{1}{l}$ is the extension per unit of length; and if the force causing the extension be f units, and a units be the sectional area of the rod or wire, then the force or stress per unit of cross-section will be $\frac{f}{a}$. Then Young's modulus is defined as—

$$\text{Young's modulus} = \frac{\text{stress}}{\text{strain}} = \frac{\frac{f}{a}}{\frac{1}{l}} = \frac{fl}{a}$$

In iron and steel Young's modulus is about 13,000 tons per square inch. In other words, a stress of one ton per square inch will produce an extension of $\frac{1}{13000}$th of the original length. (G. *Elasticitätsmodul;* F. *coefficient d'elasticité.*)

Embrittling. A term used by Howe for those elements which produce brittleness when added to steel.

Equilibrium curve. A curve showing the relation between temperature and composition, temperature and pressure, pressure and volume, etc., of any system. For alloys an equilibrium curve shows the relation between the temperature and composition of an heterogeneous system, in which the phases present are in equilibrium with each other. An approximation to the curve can be obtained by plotting a set of cooling curves; but in order to obtain a *true* equilibrium curve in this way it would be necessary for the equilibrium curve to be indefinitely slow. (G. *Gleichgewichtskurve;* F. *courbe d'équilibre.*)

Etching (*aetzen* = to corrode—Ger.) In order to develop the constitutional and crystalline structure of metals and alloys, the polished surfaces are subjected to the action of suitable reagents—nitric acid, iodine, sulphuric acid, hydrochloric acid, etc. This action is termed etching. (G. *Aetzen;* F. *attaque chimique.*)

Etching figures. Figures, generally hollowed-out pits, obtained by suitably etching crystalline surfaces, polished surfaces, or the surfaces of cleft crystals. They have a close connection with the orientation of the surfaces of the crystals. If the crystals are equivalent in form and orientation, the figures will be uniform; if not, the figures will be different. Etching figures are very useful for deciphering the crystalline structure of a "crystalline body." In amorphous bodies there are no etching figures. Very often their size and form depends upon the duration of the etching process, and on the etching medium employed; hence etching figures are not considered to be identical with the crystal elements which build up the crystal. (G. *Aetzfiguren;* F. *contours d'attaque.*)

Eutectic alloy (*εὔτηκτος* = easily melted or liquefied). A term used by Guthrie, in 1875, to indicate that mixture of two substances which has a lower melting-point than any other mixture of the same constituents.

All eutectics have a lower melting-point than that of the mean of their constituents. Eutectic alloys have usually one of three different structures—"curved plates," "flat plates," and honeycombed or cellular. As a rule, after polishing and etching, eutectics have a mother-of-pearl or opal appearance when viewed by oblique illumination. Many eutectics take on crystalline forms during solidification. (G. *eutektisch; F. eutectique.*)

Eutectic point. The common point of intersection of two inclined branches, and an approximately horizontal line in the freezing-point curves. The horizontal line is called the *eutectic line.* The alloy which has the composition corresponding with the eutectic point is called an *eutectic alloy;* before solidification, a *eutectic solution;* after solidification, a *eutectic mixture;* the temperature at which the eutectic alloy solidifies is called the *eutectic temperature.* (G. *eutektischer Punkt;* F. *pointe eutectique.*)

Face. A bounding plane surface of a crystal.

Fatigue (*fatigare* = to fatigue). When a metal is strained just beyond the elastic limit it may recover its original form on standing some time. The metal is then said to be fatigued. (G. *elastische Nachwirkung;* F. *fatigue.*)

Ferrite (*ferrum* = iron). Term proposed by H. M. Howe for iron. The term is now used for that part of steel or iron containing no carbide, or at least not more than a trace in solid solution. It covers, therefore, iron which may or may not contain silicon, manganese, nickel, etc., which form solid solution or isomorphous crystallized mixtures with iron. Ferrite is the softest structural constituent. It is unmistakably recognized as the production of cuboidal etching figures after treatment with nitric acid or copper-ammonium chloride (1 : 12) solution. (G. *Ferrit;* F. *ferrite.*)

Fibrous. Thread-like. Composed of fibres or threads. Fractured surfaces of some metals may indicate a false fibrous structure. The fibrous fractured surface may be the result of tension, which draws out the crystal grains into threads or fibres. (G. *fasrig, sehnig*; F. *fibreux.*)

Fissile (*fissus*, from *findere* = to split). Can be split into laminæ. (G. *blättrig spaltbar*; F. *clivable.*)

Foliated (*folium* = a leaf). Composed of thin layers or plates. (G. *blättrig*; F. *lamellaire.*)

Fracture (*frangere* = to break). The broken surface of a metal or alloy. (G. *Bruch*; F. *cassure.*) It may be conchoidal (*q.v.*); fibrous (*q.v.*); hackly (*q.v.*); rough (G. *rauh*; F. *inégale*); smooth (G. *eben*; F. *unie*); splintery (G. *splittrig*; F. *ecailleuse.*)

Freezing-point curve. A graphic representation of a set of cooling curves of a series of alloys of two or more substances when the temperature and composition are co-ordinates. See "equilibrium curves." (G. *Erstarrungspunkteskurve, Gefrierpunktskurve*; F. *courbe de fusibilité.*)

Friable (*friare* = to rub to small pieces). Easily crumbled or powdered. (G. *bröcklig*; F. *friable.*)

Gamma iron, or γ-iron. An allotropic non-magnetic condition of pure iron existing at temperatures above 850° C. It crystallizes in the cubic system, and its crystalline forms are combinations of the cube and octahedron (more frequently the latter) derived from the cube. In passing from β- to γ-iron an evolution of heat occurs. (G. *Gamma-eisen*; F. *fer gamma.*)

Glass-hardness. The greatest degree of hardness steel is capable of receiving on quenching from above Ar_1. (G. *Glasharte*; F. *dureté du verre.*)

Gliding plane. A definite direction in a crystal in which the molecules glide over one another. A distinction is drawn between "deformations occurring with twin formations" and "deformations by translation." If a change of form has occurred, due to twin formation, this can be traced by means of etching figures subsequent to polishing the material. This cannot be done, however, in the case of a change of form by "slip." The change is then only noticeable if the deformation occurs subsequent to the polishing. It is rendered apparent by slip-bands. These disappear immediately on etching, and no further trace is to be seen. The etching figures are not altered in appearance from the former ones. (G. *Gleitfläche ; F. plan de clivage.*)

Globulite (*globus* = a globe). In mineralogy, a rudimentary crystal, spherical in shape; in crystallography, the first visible nucleus of a growing crystal in a crystallizing solution.

Grain (*granum* = a small particle). A grain may or may not be crystalline; it may be rounded or irregularly shaped; separate or joined to other grains. The term is often used in reference to the fracture of steel—coarse grain, fine grain, etc. As all such steels are crystalline, the term "grain" when applied to metals is often regarded as a contraction for "crystal grain" or "crystalline grain." (G. *Korn ;* F. *grain.*)

Granular. Composed of grains or irregular crystalline particles, *e.g.* sandstone, marble, granite, iron, and steel. (G. *körnig ;* F. *grenu.*)

Granulitic. A term applied by Michel-Lévy to holocrystalline rocks composed of juxtaposed grains, all approximately the same size, and independently oriented. Iron and steel and many other alloys have these characters. (G. *granulitisch ;* F. *granulitique.*)

Grinding (O.E.). The process of preparing smooth surfaces by abrasion. (G. *Schleifen ;* F. *adoucir.*)

Ground-mass. The matrix of a rock in which crystals are embedded. The mass which preponderates. (G. *Grundmasse ;* F. *masse fondamentale.*)

Hackly (O.E.). Rough. Having fine, short, sharp points on the surface. Annealed steels have a hackly fracture. Coarse grained. (G. *nackig ;* F. *naché.*)

Hardening (O.E.). The process of heating steel to above Ar_1 and suddenly quenching in water. (G. *Härten ;* F. *trempe.*)

Hardenite. Martensite in the form of a eutectic solution. The term was first applied by Charpy (1897) to martensite with 0·89 per cent. of carbon. (G. *Hardenit ;* F. *hardenite.*)

Hardness. The resistance offered by a body to the separation of its particles. The hardness of a mineral is measured by the force required to scratch it with a steel point or other sharp-pointed fragment of some harder mineral. The results obtained from one and the same mineral vary slightly with the crystalline face experimented upon, and even with the direction on one and the same face. (G. *Härte;* F. *dureté.*)

Relative hardness may be expressed by reference to (i.) Mohs' scale :

1.—Talc.
2.—Rocksalt.
3.—Calcite.
4.—Fluorspar.
5.—Apatite.
6.—Orthoclase.
7.—Quartz.
8.—Topaz.
9.—Corundum.
10.—Diamond.

(ii.) Behrens uses sharply pointed needles of different degrees of hardness to determine the relative hardness. The materials employed have the following values on Mohs' scale :—

1·0.—Lead.
1·7.—Tin.
2·0.—Tin with iron.
1·5–2·2.—Hard lead.
2·5.—Zinc.
3·0.—Copper.
3·1.—Brass wire.
3·3.—Gun metal.
3·5.—Bronze with 12 per cent. tin.
3·7.—Bronze with 18 per cent. tin.
3·7–3·9.—Iron wire.
5·0–5·5.—Sewing needles.
4·0.—Needles tempered yellow.
5·0.—Needles tempered blue.
6·0.—Drill steel tempered yellow.
6·2–6·5.—Chrome steel.
7·0–7·3.—Ferro chrome.

(iii.) Brinell's method is described in *Journ. Iron and Steel Inst.*, 59. i. 269, 1901. See "Natural hardness," "glass hardness," "tempered hardness."

Heating curve. A graphic representation of the thermal changes which occur when solid substances are heated. Time and temperature are the co-ordinates. See "Cooling curve," "Equilibrium curve." (G. *Erhitzungskurve; F. courbe d'échauffement.*)

Heat-tinting. The process of heating polished surfaces of metals and alloys in air or other gas until the constituents become differently coloured. (G. *Anlassen;* F. *oxydation par chauffage.*)

Heat-tints. The tints produced by heat-tinting. (G. *Anlauffarben;* F. *colorations de recuit.*)

Holocrystalline (ὅλος = whole). Composed wholly of crystalline material, having no interstitial matter. Pure iron, copper, solid alloys, etc., are holocrystalline. (G. *vollkrystallin;* F. *holocristallin.*)

Honeycombed. Unsound from blowholes in castings, alloys, etc. (G. *blasig, bienenwabig, wabig;* F. *venteux.*)

Hot-short. The brittleness of steel when worked hot.

Hypereutectic steel (ὑπέρ = over, above). Steel containing more than the eutectic proportion 0·9 per cent. of carbon.

Hypoeutectic steel (ὑπό = under, beneath). Steel containing less than the eutectic proportion 0·9 per cent. of carbon.

Hysteresis (ὑστερεῖν = to lag behind). The persistency with which certain bodies tend to retain a previous condition. Retardation of magnetization (magnetic hysteresis). Ewing also uses the word in the more general sense of a dissipation of energy occurring in any cycle of operations. (G. *Hysteresis;* F. *hysterésis.*)

Idiomorphic (ἴδιος = peculiar; μορφή = form). Crystals which have developed their external form freely. (G. *idiomorph;* F. *idiomorphe.*)

Imbricated (*imbricare* = to cover with tiles). Overlapping like the slates of a roof. Such structures are often developed on the surfaces of polished metals and alloys by etching. (G. *dachziegelartig;* F. *imbriqué.*)

Inclusions (*includere* = to shut in). Many metals contain inclusions of gas and mechanically suspended foreign matter. (G. *Einschlüsse*; F. *inclusions*.)

Intercrystalline (*inter* = between). Between crystals. Applied to eutectic and other substances in certain alloys surrounding the crystalline grains. The term is often synonymous with "intergranular." (G. *zwischen Krystallen liegend oder verlaufend*; F. *intercristallin*.)

Intergranular (*inter* = between). Between grains. (G. *zwischen Körnern liegend oder verlaufend*; F. *intercellulaire*.)

Interpenetration. The infiltration of more infusible matter between crystalline faces. It is probable that the harmful effects of segregation are due to the natural strength between crystalline faces being destroyed by the interpenetration of weak and brittle substances such as iron sulphide and iron phosphide. (G. *Durchdringung*; F. *pénétration*.)

Intracrystalline (*intra* = within). Within or inside the crystals.

Isomeric (ἴσος = equal; μέρος = part). Formerly applied to all bodies of equal molecular weight, but now the term is restricted to bodies which not only possess identical molecular weights, but are also of similar chemical type and possess different physical and chemical properties. (G. *isomerisch*; F. *isomérique*.)

Isomorphous (ἴσος = equal, μορφή = form). A term applied to crystals similar in form. It is also applied to substances which crystallize together to form a homogeneous whole, even though the two constituents do not crystallize in the same form. See "Mixed crystals." (G. *isomorph*; F. *isomorphe*.)

Isomorphous mixture. Bodies which crystallize together to form a homogeneous whole.

Jog (O.E.). A term used by Howe to express the sudden limited extensions which certain metals undergo at different tenacities. The term was derived from the peculiar shape of the curve obtained when the metal is subjected to tension. Under proper conditions, iron and steel of certain classes, if they have previously been neither worked cold, nor hardened by quenching, give string diagrams with a well-marked bend where serious permanent set first occurs. This bend, of which the shape varies much, is called the "jog."

Jogless. Refers to iron or metals whose stress-strain diagram has not this peculiar inflexion. The term "smooth" might be misunderstood.

Joint (O.E.). The planes of junction of crystalline grains. (G. *Fuge*, *Korngrenze*; F. *joint.*)

Lamella (*lamina* = a plate). A thin plate; *e.g.* plates of graphite in grey pig iron, and of cementite in pearlite. (G. *Plättchen*, *Blättchen*; F. *lamelle.*)

Lamellar (*lamina* = a plate). Divisible into thin plates. (G. *blättrig*; F. *lamellaire.*)

Lamina. A thin leaf-like plate. (G. *Blättchen*; F. *lame.*)

Lanceolate (*lanceola* = a little lance). Lance-shaped; tapering gradually. (G. *lanzettlich*; F. *lancéolé.*)

Lap (O.E.). A portion of iron or steel folded over on itself; the walls are oxodized and cannot unite. A lap is caused by careless hammering, or by badly porportioned grooves in rolls, or by careless rolling, or projections on the ingots. (G. *Falz*; F. *crique.*)

Lattice structure. A structure developed on etching Hadfield's manganese steel and certain other metals. (G. *gitterförmig Structur*, *Netzwerk*; F. *treillis.*)

Lenticular (*lens* = a lentil). Shaped like a lens. (G. *linsenförmig*; F. *lenticulaire.*)

Liquation (*liquare* = to melt). The flowing out from partially solid metals or alloys of a portion of the still fluid mass. (G. *Saigerung*; F. *liquation.*)

Lustre (*lustrare* = to purify). A term used in describing the character of the reflections obtained from the fractured surfaces of minerals and rocks. (G. *Glanz*; F. *éclat.*) There are several kinds: adamantine (G. *Diamant–*; F. *adamantin*); greasy (G. *Fett–*; F. *gras*); metallic (G. *Metall–*; F. *métallique*); pearly (G. *Perlmutter–*; F. *nacré*); resinous (G. *Harz–*; F. *résineux*); silky (G. *Seiden–*; F. *soyeux*); vitreous (G. *Glas-*; F. *vitreux*); waxy (*Wachs–*; F. *cireux*).

Macles (*macula* = a spot). Synonymous with twin crystals. (G. *Zwillinge*; F. *macles.*)

Macroscopic (μακρός = large). A term used in contradistinction to microscopic, to imply that the character in question is visible to the naked eye. (G. *makroskopisch*; F. *macroscopique.*)

Margarite (μαργαρίτης = a pearl). Vogelsang's name (*Die Krystalliten*, Bonn, 19, 1875) for the linear arrangement, like strings of beads, assumed by crystallites.

Martensite (in honour of A. Martens). A constituent of steel produced when small samples are quenched in cold water. The structure characteristic of polished and etched hardened steels. It has the appearance of interlacing rectilinear fibres frequently arranged so as form triangles. The structure is very fine in 1 per cent. carbon steel, and coarse in 0·45 per cent. carbon steel. Some regard martensite as a solid solution of carbon in iron; Jüptner considers it to be a solid solution of iron carbide in iron; Campbell gives it the composition C_2Fe_6. (G. *Martensit*; F. *martensite.*)

Massive. A term used in contradistinction to "stratified." The term has been used for free cementite as distinct from that in pearlite. The term does not imply that the material is homogeneous. (G. *massiv*; F. *massif.*)

Matrix (*mater* = mother). This term embraces "mother substance" and eutectic. (G. *Grundmasse*; F. *magma.*)

Megascopic (μέγας = great). See "Macroscopic."

Metallography (*metallum* = a metal). A description of the structure of metals and their alloys. The science which deals with the composition, constitution, structure, and physical properties of metals and alloys, but does not include the art of metallurgy. That branch dealing with iron and its alloys has been called "siderology." (G. *Metallographie*; F. *métallographie.*)

Metallurgy. The art of working metals comprising the whole process of extracting them from their ores, smelting, refining, etc. (G. *Hütenkunde*; F. *métallurgie.*)

Melting-point curve. Identical with the freezing-point curve, *q.v.* (G. *Schmelzpunktskurve;* F. *courbe des points de fusion.*)

Mixed crystals. A term used for two or more substances which crystallize together as a homogeneous whole. The homogeneous solution of two or more crystallized bodies while in a solid state. From the point of view of the phase rule these form a single phase. (G. *Mischkrystalle;* F. *cristaux mêlés.*)

Mother liquid. During the process of congelation of any system consisting of several substances in a state of solution, a portion of the solution remains in a fluid state after the separating out of solid crystals; this liquor is termed "mother liquor," or "mother liquid." In systems consisting of two constituents with a eutectic point, the composition of this liquid approximates as congelation proceeds to that of the eutectic mixture, and quite attains to this composition before the whole mass passes into the solid state. (G. *Mutterlauge;* F. *liqueur-mère.*)

Natural hardness. The original degree of hardness possessed by steel before quenching above Ar_1. (G. *Naturhärte;* F. *dureté naturelle.*)

Needle. See "Acicular." (G. *Nadel;* F. *aiguille.*)

Non-eutectic cementite. That part of cementite in iron and steel which is external to the pearlite in high carbon steel.

Orientation (*orire* = to rise). The relative direction of the axes of crystals or of the axes of elasticity in two or more crystals, or the relative position of these axes with regard to a certain surface or line; for instance, the polished surface or a cleavage plane, etc. (G. *Orientirung;* F. *orientation.*)

Osmotic pressure (*ὠθεῖν* = to push). When two liquids are separated by the intervention of a porous diaphragm, a flow of liquid takes place from one side to the other, or sometimes an unequal flow of the two liquids in opposite directions. This phenomenon is termed "osmose," and the pressure exerted by a dissolved substance in its solution is termed its osmotic pressure. (G. *osmotischer Druck*; F. *pression osmotique.*)

Pearlite. A term applied by Howe for the "pearly constituent" of steel discovered by Sorby. It consists of alternating plates of cementite and ferrite, or sorbite, or grains of cementite embedded in ferrite or sorbite. Jüptner considers the cementite of pearlite consists chiefly of the carbide C_4F_{12}, but that sorbite possibly contains C_3Fe_9. This view is in harmony with E. D. Campbell's data. (G. *Perlit*; F. *perlite.*)

Pearly constituent. Sorby's original term for what is now called pearlite. Named owing to its peculiar mother-of-pearl like colours.

Phase. A phase is defined to be a mass chemically or physically homogeneous, or as a mass of uniform concentration. (G. *Phase*; F. *phase.*)

Phase rule. A rule for finding the number of phases which can exist in a system containing a certain number of components, and having a certain number of degrees of freedom. It connects together the number of components degrees of freedom, and possible phases in equilibrium. The phase rule states that in a system of n components there can exist in equilibrium $n + 2$ phases if the system be nonvariant, $n + 1$ if it be univariant, n if it be divariant, etc. (G. *Phasenregel*; F. *loi des phases.*)

Pipe (A.S.). A cavity formed in the central upper part of an ingot. (G. *Lunker*, *Schwindungshohlraum*; F. *retassure.*)

Polish attack. When an alloy contains two or more constituents of different degrees of hardness, by long-continued friction on a soft polishing surface, they are worn away in different degrees, the hardest constituent being least acted upon, the softest most. The surfaces have all the appearance of having been etched. (G. *Reliefpolieren*; F. *polissage en bas-relief.*)

Polish etching. The process of acting upon polished surfaces of metals by friction on parchment moistened with a sol. of ammonium nitrate, so as to reveal the structure. Sorbite, troostite, and martensite are coloured; ferrite and cementite remain white. (G. *Aetzpolieren*; F. *polissage attaque.*)

Polishing (*polire* = to polish). The process of preparing perfectly bright and smooth surfaces free from even microscopic scratches. (G. *Polieren*; F. *polissage.*)

Polyhedral (πολύεδρος = many sides). Applied to crystal grains having two or more different shapes.

Polymorphism (πολύς = many; μορφή = form). The property possessed by some substances of assuming two or more forms of molecular structure. (G. *Polymorphismus*; F. *polymorphisme.*)

Prismatic (πρίσμα = prism). Refers to crystals which occur in columnar forms giving lath-shaped sections. (G. *prismatisch, säulenförmig*; F. *prismatique.*)

Pseudomorphous (ψευδής = false; μορφή = form). A false form, applied to minerals possessing a crystalline form other than their own, which they have obtained by displacement or alteration of the original mineral. Osmond has recently used the term for crystalline grains in iron, where their forms are determined by mutual interference. (G. *pseudomorph*; F. *pseudomorphe.*)

Radiating (*radiare* = to emit rays). When the fibres are arranged around a central point like the spokes round a wheel.

Recalescence (*re* = anew; *calor* = heat). The phenomenon of evolution of "internal" heat, which occurs when iron and steel cool through critical zones. (G. *Recalescenz*; F. *recalescence.*)

Red-short. Steel which is brittle on working at a red heat. (G. *Rothbrüchig*; F. *cassant à chaud.*)

Reticulated (*reticulum* = a little net). The appearance of network traversed by two sets of parallel lines. (G. *netzförmig, netzartig*; F. *réticulé.*)

Rotation effect. An expression used by Heycock and Neville to describe the lighting up and darkening of the crystalline grains in the etched surface of polished metal, when rotated before oblique rows of light.

Ewing and Rosenhain use the term "selective effect of oblique light."

Scaly. In plates which overlap one another like the scales of a fish. (G. *schuppig*; F. *scailleux*.)

Schillerization (*Schiller* = play of colours—Ger.). Refers to the peculiar bronze-like lustre, "schiller," in certain minerals, due to the presence of minute inclusions in parallel positions.

Schlerometer (σκληρός = hard). An instrument for the determination of the relative hardness of bodies. (G. *Sklerometer*; F. *scléromètre*.)

Scoriaceous (σκῶρ = dung). Having the appearance of scoriæ. Term used to describe unknown "inclusions" in metals and alloys. (G. *schlackenartig*, *schlackig*; F. *scoriacé*.)

Scoriæ. Cinder or slag from metallurgical processes. (G. *schlackenartiger Körper*; F. *scories*.)

Seam (O.E.). A seam is an effect caused by a blowhole, which working has brought out to the surface, and not eliminated. It usually, or always, runs in the direction of working. Seams are distinguished from laps by not being continuous; they are usually only an inch or two in length. (G. *Naht*; F. *couture*.)

Segregation (*segregare* = to separate). A term applied to the more fusible parts of alloys which are last to freeze, and are driven into certain local centres by the part which freezes first. Segregations are generally found near the centre of a casting, and are more pronounced in large masses. (G. *Ausscheidung*, *Saigerung*; F. *ségrégation*.)

Short. See "Cold-short," "Hot-short," and "Red-short."

Siderology (σίδηρος = iron). The branch of metallography which treats of iron and its alloys.

Skeleton crystals (σκελετός = a dried body). The incipient forms of crystallization in which some metals or alloys appear when cast. (G. *Krystallskelette*, *gestrickte Formen*; F. *réseau du cristal*.)

Slag inclusions. Particles of slag enclosed in a metal. (G. *Schlackeneinschlüsse*; F. *scories enfermées*.)

Slip-bands. Microscopic appearance in the smooth surfaces of metals after straining caused by slips along the cleavage or gliding planes of the crystalline grains.

Solid solutions. Van't Hoff's term for a homogeneous mixture of two or more substances in the solid state. The mixture may be crystalline or non-crystalline. The former may be "isomorphous mixtures," or "mixed crystals." (G. *feste Lösungen*; F. *solutions solides.*)

Solidified solution. See "Congealed solutions." (G. *errstarrte Lösung*; F. *solution congélée.*)

Solution plane. Von Ebner's term (1814) for the plane of a crystal surface, which is most easily attacked when submitted to chemical action. (G. *Lösungfläche*; F. *direction de solution.*)

Sorbite. An alleged constituent of steel named in honour of H. C. Sorby. It is obtained by cooling sufficiently slowly to allow the transformation to proceed far enough and sufficiently rapid to produce but an imperfect separation of ferrite and cementite. This is done by cooling small samples in air, and then towards the end of recalescence, in cold water, or molten lead; or reheating martensite (tempering) to a blue colour. It is an intermediate form between martensite and pearlite. It gives a brown colour by the polish attack, or by iodine or dilute acids. Jüptner believes sorbite to be a solution of Fe_3C_3 in iron. (G. *Sorbit*; F. *sorbite.*)

Spherulitic structure (*sphærula* = a little sphere). Peculiar to vitreous rocks, and eutectics of rapidly cooled alloys. So called because of the presence of small spheroidal bodies—spherulites. The latter, under the microscope, seem to have a divergent fibrous structure. This structure is common with rapidly cooled eutectics: lead-tin, antimony-lead, gold-lead. (G. *sphärolithische Struktur*; F. *structure globulaire.*)

State of aggregation. A term frequently used by chemists when referring to the different forms in which matter may exist—solid, liquid, or gas.

Stellate (*stella* = a star). Radiating from a centre as in some copper-tin alloys rich in tin, in which the compound CuSn crystallizes in stellate or starlike forms. G. *Sternförmig;* F. *en étoile.*)

Superficial tension. The surface of a liquid has a greater tension than any part of the interior. The surface seems as if it were covered by a stretched elastic film. The surface tension is greater, the greater the cohesion of the liquid. (G. *Oberflächenspannung;* F. *tension superficielle.*)

Surface tension. See "Superficial tension."

Surfusion (*sur* = beyond). A transitory liquid state at temperatures below the normal freezing-point. (G. *Überschmelzung;* F. *surfusion.*)

Temper (O.E.). Term used by steel-maker. Refers to quantity of carbon present, but more generally to the colour to which hardened steel has been annealed. It is the steel-maker's measure of *initial* hardness; the steel-user's *final* hardness. (G. *Kohlungsgrad;* F. *degré de recuit*). The temper may be: low temper (G. *weich*); medium or high temper (G. *mittelhart, hart*); straw-yellow (G. *strohgelb,* F. *jaune paille*); brown (G. *braun,* F. *brun*); violet (G. *violett,* F. *violet*); blue (G. *blau,* F. *bleu*); low temper steel (G. *weiches Flusseisen*); medium temper steel (G. *mittelhartes Flusseisen*); high temper steel (G. *harter Stahl Flusseisen*).

Tempering colours. Colours which appear on iron or steel surfaces when heated in air. (G. *Anlauffarben, Anlassfarben;* F. *couleurs de recuit.*)

Tenacity (*tenere* = to hold). The resistance to rupture presented by a substance whose elastic limit has been exceeded. (G. *Zugfestigkeit;* F. *ténacité.*)

Troostite. An alleged constituent of steel named in honour of L. Troost, a French chemist. It is obtained by quenching steel at certain temperatures. Like sorbite, it is supposed to be an intermediate form between martensite and pearlite. The transitional stages being: martensite → troostite → sorbite → pearlite. It is softer than martensite, and more easily attacked by acids. It gives a brown colour when treated by the polish attack. It is coloured dark by a solution of 1 c.c. of hydrochloric acid in 100 c.c. of alcohol, while martensite is not affected. It is considered, by some, to be a solution of Fe_9C_3 in iron. (G. *Troostit;* F. *troostite.*)

Twinned (O.E.). A crystal is twinned when two portions of the same individual, or two different individuals are related to one another according to a definite law. (G. *verzwillingt, zwillingsbildung;* F. *hémitrope, maclé.*)

Vesicular (*vesicula* = a little blister). Containing small holes. (G. *mit Bläschen besetzt;* F. *vésiculaire.*)

Widmanstäten figures. Certain patterns which appear on etched surfaces of meteoritic iron. Named after A. B. Widmanstätten. J. O. Arnold and A. McWilliam, *Nature*, 71. 32, 1904.

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